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史特拉底瓦里與義大利歷史小提琴的分析比較：

從材料化學與結構設計到發聲性質

Comparison of Stradivari and old Italian violins:

from material chemistry and construction design

to voice quality

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國立臺灣大學碩士學位論文
口試委員會審定書

（論文中文題目）史特拉底瓦里與義大利歷史小提琴的分析比較：從材料化學與結構設計到發聲性質

（論文英文題目）Comparison of Stradivari and old Italian violins: from material chemistry and construction design to vocal quality

本論文係沈昱平君（學號R03223138）在國立臺灣大學化學系完成之碩士學位論文，於民國107年5月25日承下列考試委員審查通過及口試及格，特此證明。

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誌謝

研究的時間很快得就過去了，相較於歷史名琴所流傳的時日，自己的這段學術經歷更顯得如夢如幻，相當不真實，聽著各把名琴的聲音，歲月似乎就停滯了……

奇美博物館的數位典藏計畫說道：一把名琴，牽起了素昧平生的製琴師與演奏家、甚或繫起了百年後的演奏家與蒐藏家。我何其有幸，能見證小提琴的歷史發展。十六世紀中旬，義大利北部人阿瑪第發明現代小提琴，他的家族與學徒在兩百年後皆致力於小提琴的發展，突破了人類對音樂的理解。十九世紀初期，義大利北部人塔瑞西歐徒步至巴黎，將義北的歷史名琴推廣至全歐洲，而後各地的藏琴師們，投盡資產傾盡歲月的搜集名琴，保存與傳承那些超越三百年歲數的文化瑰寶，自西元一九九零年起，奇美博物館加入了名琴收藏的行列，因此，我才能有緣分邂逅這些瑰寶。現代，美國的畢辛吉爾與納吉瓦里教授，投入了三十年的光陰，發展各種技術量測小提琴的震動，使人類對於音樂物理的認識更加邁進，在戴桓青教授的帶領下，我有幸能一窺提琴研究的奧妙，在這領域中成長學習。人類能不斷成長，正是因為許多人們不斷地做著自己喜愛的事，樂而不能止，三月而不知肉味，不為名利矇蔽雙眼，不被人類經驗束縛，不知不覺間，就將人類推向了新的高度。

感謝戴桓青教授提供實驗室的環境使我能夠學習，感謝家人讓我能夠心無旁騖的投入，感謝李國乾學長、林哲宏學弟等實驗室夥伴還有社會中各位有心人士的支持，我才能進行這份研究，期待自己的這份研究，能在往後給予人們些微的啟發。

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中文摘要

小提琴演變的五百年歷史中，在結構設計與聲音特性上，有兩個眾所皆知的里程碑。第一個里程碑是安德雷亞•阿瑪蒂(Andrea Amati, 1505-1577)十六世紀初期在義大利克里蒙納小鎮(Cremona)所發明的現代小提琴。爾後有許多制琴師嘗試改變阿瑪蒂的結構設計，但都在聲音特性上調整失敗，因此小提琴的結構設計並未有太大的演變。第二個里程碑是安東尼奧•史特拉底瓦里(Antonio Stradivari, 1644-1737)在十八世紀初期的成就，史特拉底瓦里師承阿瑪蒂家族，微調其結構設計並改進聲音特性。過去兩個世紀中，許多著名的獨奏家獨鍾於演奏史特拉底瓦里的小提琴，而相較其餘製琴師，史特拉底瓦里小提琴的構型也最常被模仿。然而，從阿瑪蒂至史特拉底瓦里的演進之路上，其幾何結構的演變雖然容易量測，其聲學性質的變化卻仍未被定義。

我們錄製了由阿瑪蒂至史特拉底瓦里時代間的十五把義大利歷史小提琴，以及男女聲的半音階。並利用線性預測編碼方法進行泛音特徵的比對。本實驗的義大利小提琴中，兩把最早的典型(1570 Andrea Amati 與 1560 Gasparo da Salo)都在 5000 赫茲以下呈現出四個類似人聲的共振峰(F1-F4)，其 F1 與 F2 對應到國際音標元音圖(IPA vowel diagram)的中央區域，F3 與 F4 則對應於男性的歌唱。因此，小提琴的發明者們，極可能是藉由模仿男性歌唱的聲音而達到了第一個里程碑。從 F1 至 F4，相較共振峰類似男中音/男低音的其餘歷史小提琴，史特拉底瓦里都呈現了更高的頻率，更類似於男高音/女低音。在國際音標元音圖中，升高的 F1 與 F2 會產生更開放與更前端的元音，使得元音聽起來更明亮更渾厚，這些獨特的元音與性別特徵符合幾世紀來人們對其不同尋常的經驗感受。傳統上，人們將阿瑪蒂至史特拉底瓦里間的聲音轉變歸因於後者較小的木板曲度，但近來的證據顯示，木材的化學處理也可能造成其特性的轉變。

關鍵字：小提琴、阿瑪蒂、史特拉底瓦里、線性預測編碼、人聲、泛音

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ABSTRACT

During the evolution of violin models over the past 500 years, there were two widely recognized design/acoustic landmarks. The first landmark was the invention of the modern violin in the early 16th century by Andrea Amati (1505-1577) in Cremona, Italy. The shape and form of the violin have evolved very little since, as numerous later attempts to alter Amati's basic design have failed to maintain the favorable acoustic qualities. The second landmark was achieved by Antonio Stradivari (1644-1737) in the early 18th century, who learned his craft from the Amati family but made slight modifications to improve the acoustics. For the past two centuries, more famous soloists have preferred to play Stradivari violins than all other makers combined. Stradivari's violin models are also copied more frequently than any other violin maker. While the geometric evolution from Amati to Stradivari models are easily measurable, the underlying acoustic properties that help define these two landmark designs remain unknown.

In this study, we recorded the chromatic scales of 15 old Italian violins, ranging from Amati to Stradivari, as well as male and female singing voices. The linear predictive coding algorithm was applied to compare their formant features. The early examples of Italian violins (1570 Andrea Amati and 1560 Gasparo da Salo) both

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showed four voice-like formants (F1-F4) below 5000 Hz. The F1 and F2 values in these early violins mapped to the central region on the international phonetic alphabet (IPA) vowel diagram, while their F3 and F4 values corresponded to those of male singing. Therefore, the first landmark design devised by the early inventors of the violin appeared to mimic the male singing voice.

Compared to other old Italian violins of which formants were similar to basses/baritones, in F1 through F4, Stradivari violins exhibited higher formant frequencies which were similar to tenors/altos. In the IPA vowel diagram, elevated F1 and F2 led to the lower vowel height and the more front vowel, shifting toward the brighter and bigger symbolism. The unique vowel and gender qualities associated with Stradivari violins appeared to correlate well with long-held opinions about their distinctive brilliance. The tonal improvement going from Amati to Stradivari violins has been historically attributed to lower plate arching in the latter,[1] but recent evidence also suggested that chemical treatment of wood may have altered its material properties.[2]

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Chapter 1 Introductions

1.1. The history of old Italian violins

The ideas for inventing violins may be borrowed from the early string instrument, such as rebecs, lutes and vielles. One of the earliest descriptions of the violins was from the Epitome musical by Jambe de Fer, published in Lyon in 1556.[3] Besides, it was said that the French king Charles Ⅸ ordered Andrea Amati to make 24 violins for him in 1560.[4] By these two descriptions above, we suggested that violins had already begun to spread through Europe since the middle of the 16th century.

In 1505, Andrea Amati was born in Cremona, Italy.[5-7] He was a luthier who began making the three-stringed bowed instruments. Because of creating the first four-stringed violins in 1542, he was credited for the inventor of modern violins. Andrea Amati only taught his two sons, Antonio Amati and Girolamo Amati, about the skills of making violins. In Cremona, the knowledge of making violins was only passed through the Amati family until the grandson of Andrea Amati, Nicolo Amati, took outside apprentices.

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Near Cremona, there was a town called Brescia(Figure 1- 1). In this town, there was a prestigious violin maker named Gasparo da Salo. He was born in 1542 and 37 years younger than Andrea Amati.[8-9] He grew in a family which was famous for playing and making string instruments. Although we didn't know how he learned to make the violins, he was referred as a violin master as early as 1568.[10] His violins were wonderfully decorated, and some of the patterns could be seen in the violins made by Antonio Stradivari. Gasparo da Salo developed the Brescian school and the master luthier, Giovanni Paolo Maggini was also his student. Hence, the Brescian and Cremona school were regarded as two of the earliest schools which made violins.

Figure 1- 1. The position of Brescia and Cremona.

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Back to the Cremona school, when the famine and the plague decimated Cremona in 1630, Nicolo Amati was the only survivor in the Amati family.[11] He had no immediate heirs and took on apprentices outside the family, and it made the Guarneri and Stradivari family rise a few decades later. We listed the relationship of important Cremona and Brescian luthiers(Figure 1- 2). All the violins we recorded in this thesis were made by these masters.

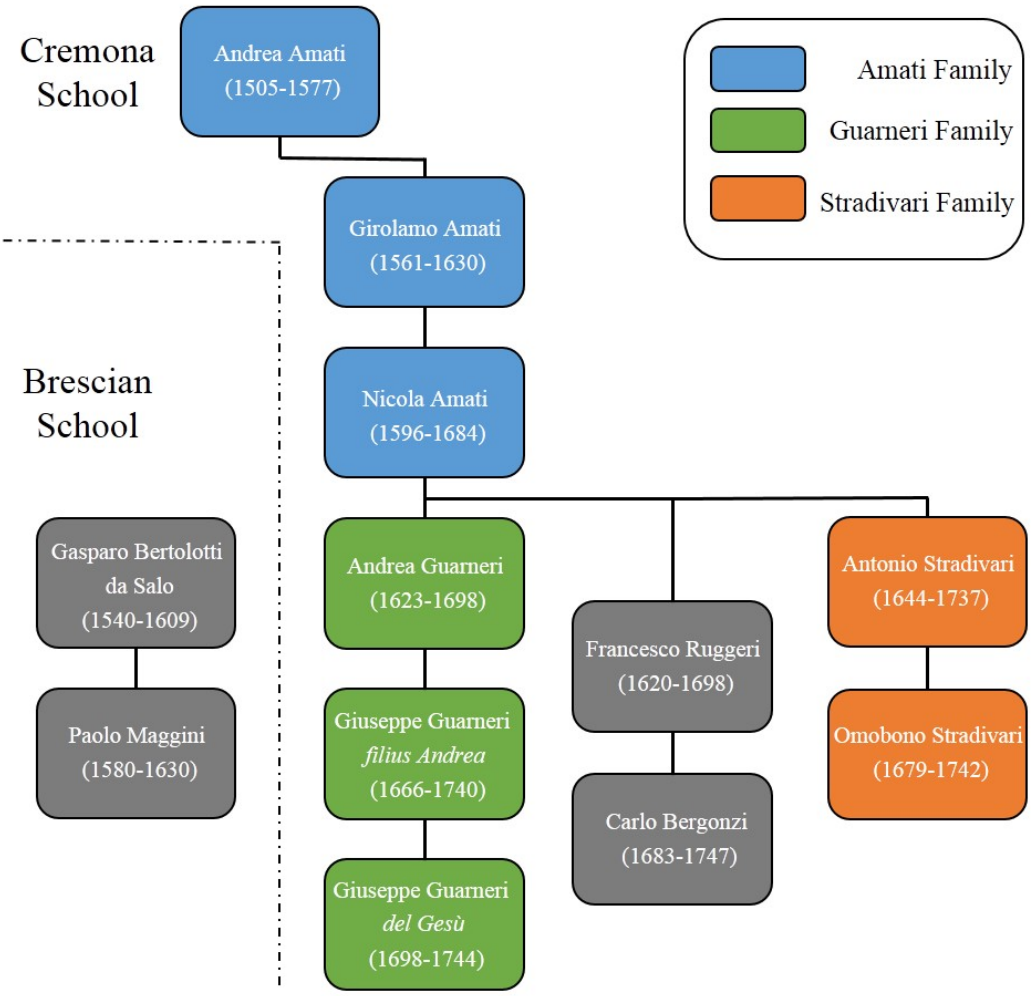

Figure 1- 2. The relationship of the Brescian and Cremona school.

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In 1641, Andrea Guarneri was living with Nicolo Amati and being instructed in the art of violin making, probably working with Francesco Ruggeri and Antonio Stradivari who were also apprentices at the same time.[12] The earliest Andrea Guarneri violins unsurprisingly closely resembled the Amati style. Later in his life, he developed his own style in not only the structure of the violins but also the varnish.[13] He then passed on these techniques to his descendants. His grandson, Giuseppe Guarneri who was known as del Gesù, was regarded as one of the most brilliant luthiers in history. Due to these fantastic violins that the Guarneri family made, their reputation was as high as the Amati family who invented the violins.

One of the other apprentices of Nicolo Amati, Antonio Stradivari, brought together his decades of experimentation, combing the powerful tone of the Brescian instruments with the clear sweet sound of the Cremonese.[14] Because of that, he was also regarded as one of the most brilliant luthiers in history, equaled only by Guarneri del Gesù. In the minds of most violinists and the connoisseurs, the best violins they have ever heard were made by either del Gesù or Stradivari. At the mention of the Cremona school, people immediately thought of these three great families: Amati, Guarneri and Stradivari.

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1.2. The collection of old Italian violins

No matter how brilliant these old Italian violins were, people would not know their beauty if no one preserved and collected these treasures. Count Cozio di Salabue (1755-1840) was the first great connoisseur and collector of violins.[15] His father owned a Nicolo Amati violin dated 1688.[14] It may cultivate his enthusiasm about rescuing the violin art from declining. Cozio was the patron of the violin maker, Giuseppe Guadagnini, who settled in Turin in 1771.[15] He systematically tracked down all the existing Stradivari violins from all over northern Italy. In his collection, the most important instruments were ten violins of Antonio Stradivari. Although he kept those he considered the most valuable, he still had to sold some of the instruments to maintain his silk merchant's shop in Turin. The old Italian violins could be repaired and preserved well due to the efforts of Cozio.

When Cozio died in 1840, Luigi Tarisio (1755-1854) acquired all his treasures.[14] Encouraged by his family in Milan and his violin teacher who owned a Stradivari violin, Luigi Tarisio was determined to collect the Cremona violins when he was young. He had tried to find the old Italian violins since 1809, and had made the people in Europe understand the value of old violins since 1827.[14] In 1827, he walked from Milan to Paris and appeared at the salon of M. Aldric, a violin maker and dealer known throughout Europe. Aldric bought a Maggini, a Francesco Ruggeri, a Storioni and two Grancinos

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from Tarisio. Soon after, Aldric invited his friends and colleagues, including George Chanot, Charles Francois Gand and Jean Baptiste Vuillaume, to admire these treasures. Therefore, the greatest authorities on violins among Europe at that time all knew the value of old Italian violins. It encouraged Tarisio to keep up his work until he died in 1855, and all his collection were bought by Vuillaume.

In brief, Cozio was the pioneer to find and collect old Italian violins. Tarisio continued Cozio's work and made the value of the old Italian violins known to all Europe. If without their efforts, these violins could not be preserved and could not be appreciated now.

In our study, the violins we recorded were all borrowed from Chi-Mei Museum. Chi-Mei Museum has been collecting the historic violins since 1990. At that time, Wen-Lung Hsu, the founder of Chi-Mei, bought the first Stradivari violin, Dushkin, from Chao-Liang Lin, a famous Taiwanese violinist. Dushkin was made by Antonio Stradivari in 1707. It was named after the owner, Samuel Dushkin (1891-1976), who collected it in the beginning of the 20^{th} century. Then, it was sold to England where Chao-Liang Lin found it. Fortunately, Dushkin became the first Stradivari violin collected in Taiwan.

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The Chimei collection has now over 1000 antique string instruments, arguably the largest in the world, including 5 violins made by Antonio Stradivari and 1 violin made by Giuseppe Guarneri.

Each historic violin has its own story. We chose two of the violins we recorded as example, one was Stradivari Elman (1722) and the other was Gasparo da Salo (1560).

Elman had the richest historical meanings in our violins. Joseph Joachim, born in Hungary, regarded as one of the most significant violinists of the 19th century, once owned this violin. Passed through some dealers, this violin had been owned by Mischa Elman for around 40 years. That was why this violin was named Elman. From 1981 to 1991, Josef Suk, a Czech violinist, owned this violin. Finally, Elman has been collected by Chi-Mei since 1991.

Gasparo da Salo (1560) was the oldest violin in our recordings. There was an original mark which was carved the completion date in the interior. The violinist who had owned this violin until 1968 was Leslie Browne in London. The next owner was Homi Kanga, who was the most remarkable western musicians came out of India. After Homi Kanga retired, Chi-Mei has collected this violin until now.

From the description above, we know that it is an amazing thing that the historical violins could still be seen and played(Figure 1- 3). There were a lot of efforts and stories in these violins, including the creating of luthiers, the buying of dealers, the repairing

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of makers, the preserving of collectors and the playing of violinists. Therefore, the dream and even the soul in the violins could be reappeared in front of us.

Figure 1- 3. The violin pictures.

Left: Gasparo da Salo (1560). Center: Dushkin. Right: Elman.

The pictures were from Chi-Mei <http://db.dacm.ntnu.edu.tw/Chimei/tw/index.html>.

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1.3. The manufacture of violins

For hundreds of years, the boards for manufacturing violin have been from spruce or maple. The plate of violin is cut from one board, which is then sawed in the middle(Figure 1- 4).[16]

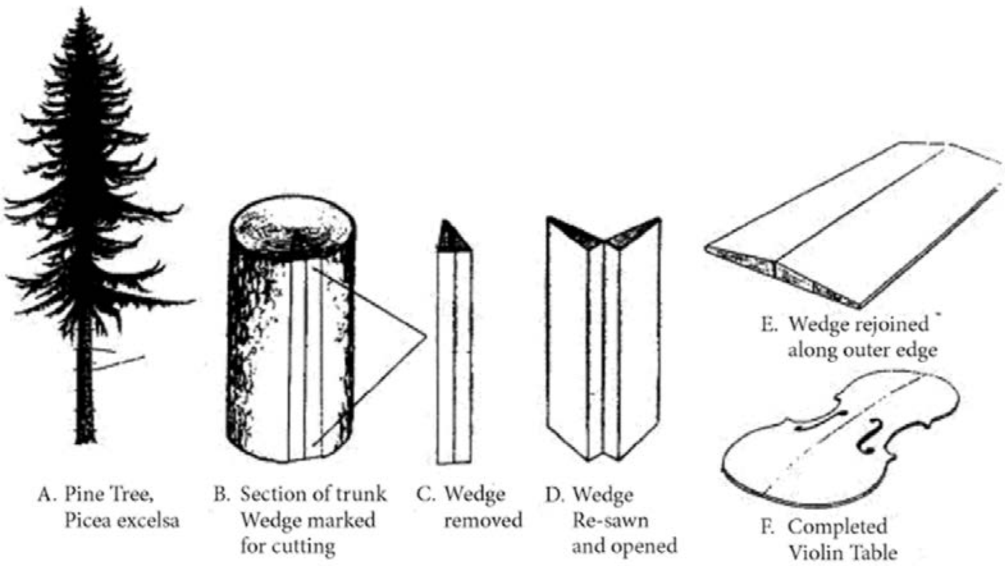

Figure 1- 4. Making the top plate from pine or spruce.
This figure is adopted from Wali et al., 2010.[16]

The basic components of a violin are shown in Figure 1- 5.[17] The resonant chamber is composed of the *top* plate made of spruce, the *back* plate made of maple, and the *ribs* which hold the two plates together. The air goes in and out the chamber from the two *f-holes* on the top plate. Inside the chamber, there are two components which influence the vibration of the plates and the air. One is the *bassbar* which is a wooden piece along the length of the top plate, and the other is the *soundpost* which is a pencil shaped wooden piece between the two plates. The corner and the end *blocks*, the *lining strips* and the *purfling* are used to strengthen and complete the chamber. The arched *bridge*

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connects the chamber and the four strings. The *tailpiece* and the *neck* are at the two ends of the *fingerboard*. The neck is attached to the *peg box* and ends in a *scroll*. Besides, to help our discussing below, we define a special part of top plate as *island*. The island is beneath the two bridge feet and between the two f-holes. This region is related to the vibration of high frequency.

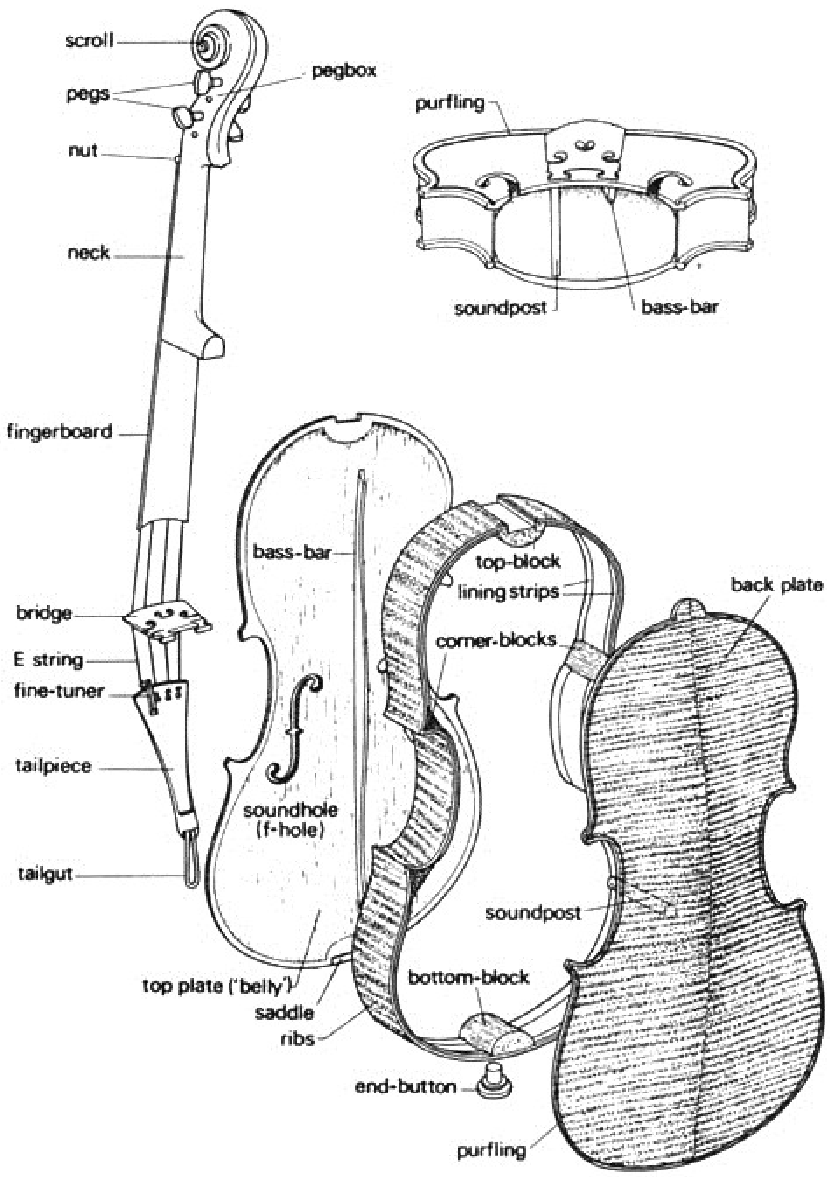

Figure 1- 5. The diagram of the violin components.

This figure is adopted from Boyden et al., 1989.[17]

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1.4. The acoustics of violins

There are four strings in a violin. The musical notes of the four open strings are G3, D4, A4 and E5 respectively. The range of the violin pitch is from G3 to E7. When we play the violin, the string produces the fundamental frequency and many related harmonic frequencies. The sting transmits the vibrations to the bridge, then to the chamber and finally to the air which we hear of. The bridge and the chamber would enhance the intensity of several specific harmonics if these harmonics match the vibration modes on them. On the other hand, the intensity of several specific harmonics would be weakened if these harmonics are correspondent to the forbidden mode of them. Bissinger associated the enhanced frequency bands to the violin structure (Figure 1-6).[18] This figure is a combination of several different experimental methods, because the influence of different violin structures can only be observed in different experiments.

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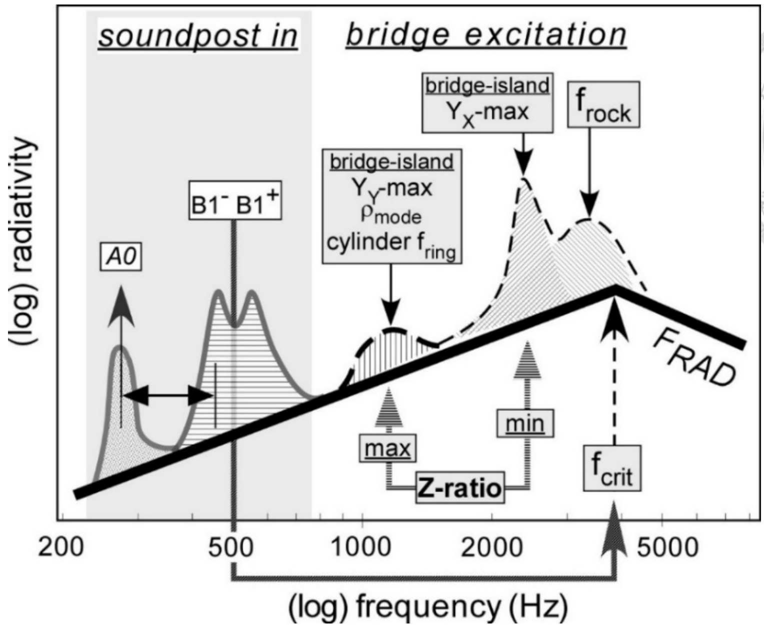

Figure 1- 6. Summary schema for "building" violin radiative profile.

A0: the air mode, produced by the resonance of the violin plates. $B1^-$ and $B1^+$: the baseball modes, produced by the resonance of the violin plates. bridge-island: the resonance produced by the bridge and the island. f rock: the rocking mode, produce by resonance of the bridge.[18]

There are two bands related to the chamber in the frequency ranging from 200 to 800 Hz. Bissinger used the modal analysis to observe these three modes, A0, $B1^-$ and $B1^+$, which are called the signature modes. In this method, a hammer is used to hit the bridge corner, and the mechanical response of the violin plates could be measured.[19] Each violin has a unique set of signature modes. Many researchers also proved it and explained it well. A0 is called the air mode and is produced by the resonance of violin plates and the air in the violin body. If we suppose the string is pulled to the right. The left foot of the bridge goes up, and the bassbar transmits the force to the top plate. The right foot of the bridge goes down, and the soundpost transmits the force to the back plate. At this time, the top moves up, and the back moves down. It expands the chamber and the air flows in through the f-holes. In the opposite mode, the string is pulled to the

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left, and the air flows out. In this kind of motion, the f-holes acts as the nose of the violin, and this is why the motion is called the breathing mode. $B1^-$ and $B1^+$ are called the baseball modes, because of the shape of the nodal lines. These modes are produced by the resonance of the violin plates. In the previous research, there have two characters, the bending and the breathing mode, with opposite phases.[20] The sum and difference combination cause the $B1^-$ and $B1^+$ modes respectively. In Figure 1- 7, the left pair shows the top and the back plate measurements while the right pair shows simplified finite element computations.[21] The two patterns are close to each other, proving the correct explanation of signature modes. In brief, the signature modes were mainly influenced by the vibration of the violin chamber.

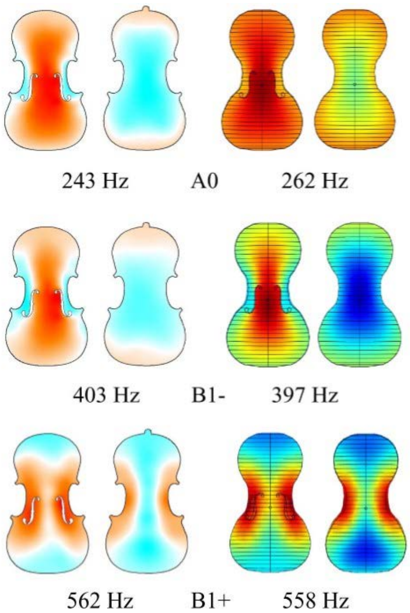

Figure 1- 7. The signature modes.

Left: Measurements. Right: Theoretical results.

The signature modes are composed of the air mode(A0) and the baseball modes($B1^-$ and $B1^+$).[21]

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In Figure 1- 6, the resonance bands from 800-5000 Hz are mainly influenced by the bridge and the islands in the frequency. Although the full explanation of this frequency range is complicated and nuanced, that the resonance of the bridge leads to this feature is not controversial.[22] As noted earlier, the soundpost is not directly linked to the right foot of the bridge but slightly displaced from it. Besides, in this frequency range, the inertia of the soundpost and the back plate become significant enough to reduce the vibration. Therefore, the soundpost can be seen to be stationary and acts as a fulcrum to allow a teeter-totter motion of the bridge and the top plate. This motion is called the rocking mode and assigned around 3500 Hz in Figure 1- 6. Several possible modes of bridge rocking have been proposed in Figure 1- 8.[23]

Figure 1- 8. Sketches of the resonances of the bridge.
This figure is adopted from Bissinger et al., 2006.[23]

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Besides, Bissinger used zero-mass-loading laser scans to analyze the mechanical response of the islands, finding that there was a vibration peak around 1200 Hz in the Y-direction (perpendicular to the violin plate) and a vibration peak around 2500 Hz in the X-direction (across the violin) (Figure 1- 9).[24] Compared with the bridge vibration, when the energy is transferred from the bridge to the island, Bissinger found stronger vibration on the island than on the bridge. It suggested some excitation due to the X motion of the island happened (Figure 1- 10).[24] Hence, he assigned the band in 2500 Hz which was traditionally called bridge-hill (BH) as the bridge-island peak.

Finally, Bissinger used the far-field radiativity scans in an anechoic chamber to measure the pressure response. Compared with the total mechanical response of the violin, he obtained a parameter, the fraction of the vibrational energy radiated (FRAD), finding that the most effective frequency was related to B1 mode.[18]

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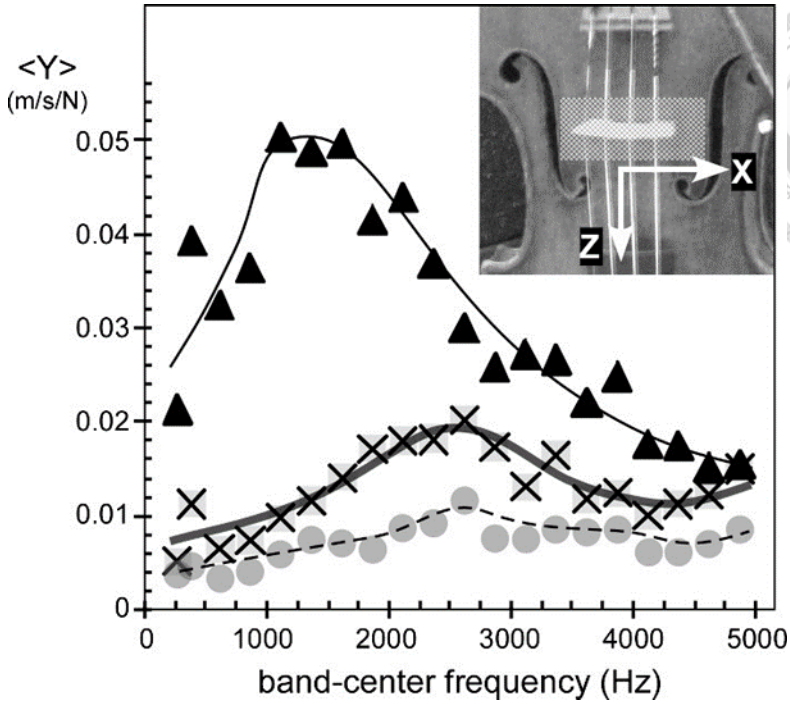

Figure 1- 9. The vibration of the islands.

Cross: X-direction. Triangle: Y-direction (perpendicular to the violin plate). Circle: Z-direction.[24]

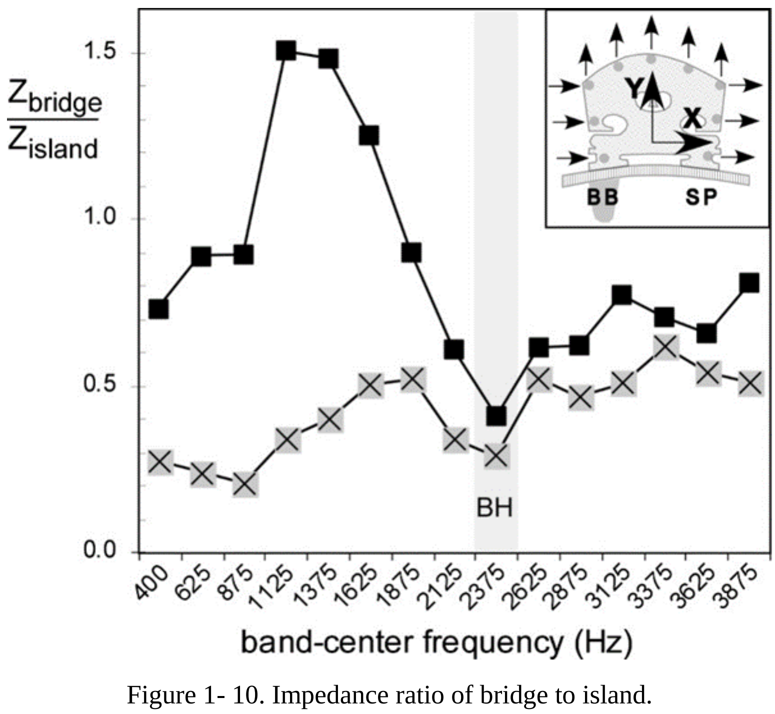

Figure 1- 10. Impedance ratio of bridge to island.

Cross square: X-direction. Solid square: Y-direction. BH is the abbreviation of bridge hill.[24]

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Based on the works of Bissinger, the knowledge of the violin acoustics is extended far, Then, people want to know how the acoustics evolved and what is the relation between the acoustics and the construction design or the material chemistry.

To get the answers, we go back to the time when the violin was created. After the invention of the modern violin by Andrea Amati, the shape and form of violins has been almost fixed. As time went on, the shape had evolved little. Chitwood used linear discriminant analysis to study more than 7,000 violins. He separated luthiers by the shape attributes and made hierarchical clustering (Figure 1- 11).[25] The four major groups have been visualized (Figure 1- 12).[25] Nevertheless, as the saying of Chitwood, the acoustics of violins are little influenced by the body shape, compared to other traits, such as arching patterns, thickness distribution, and wood properties. The body shape may be more influenced by the personal styles and the customer demands.

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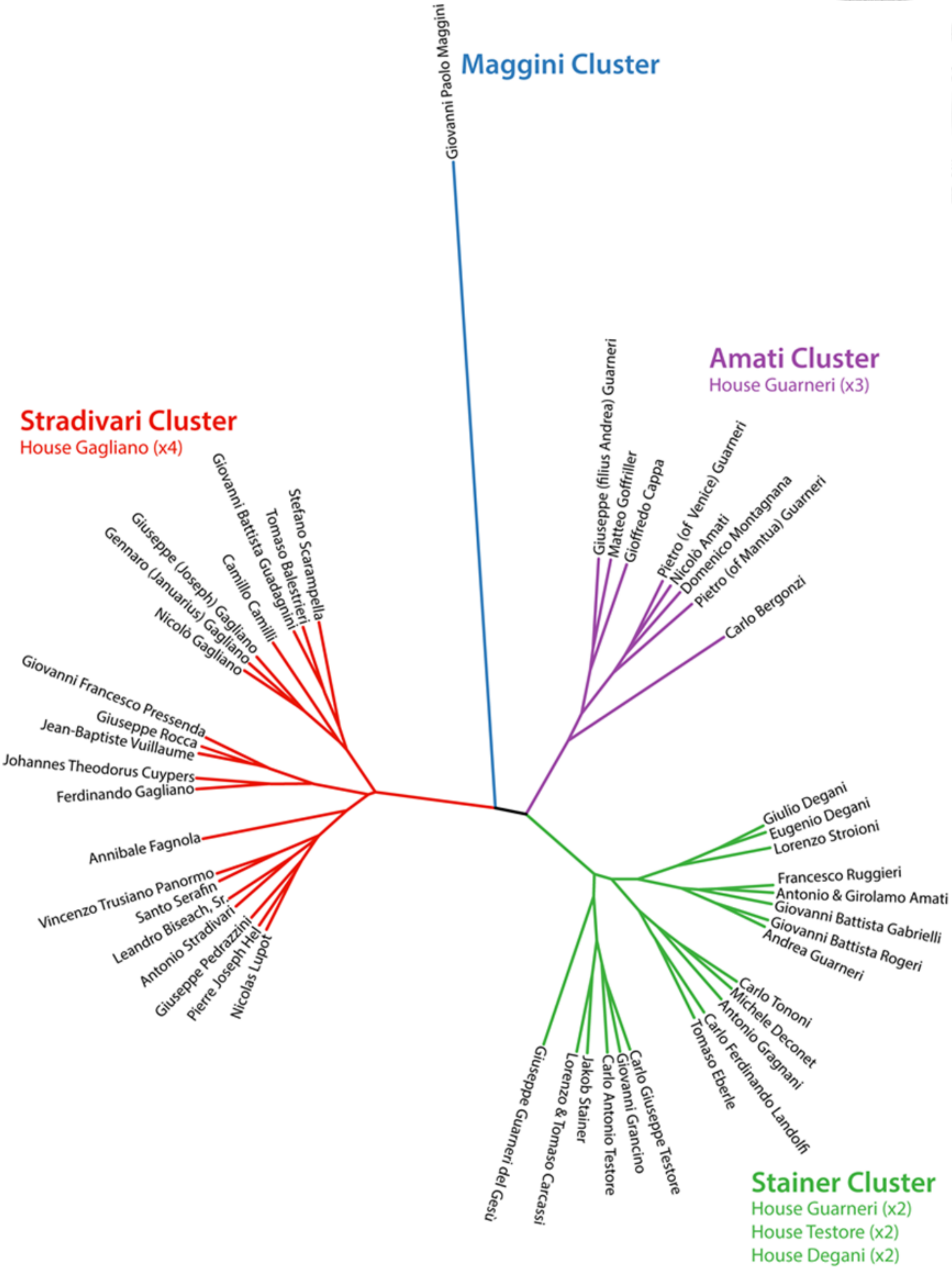

Figure 1- 11. Hierarchical clustering of violin shape.

Clustering based on averaged harmonic coefficients by prolific luthier (.45 violins). Four main clusters, named by prominent luthiers they contain, are indicated by color. Blue, Maggini cluster; red, Stradivari cluster; purple, Amati cluster; green, Stainer cluster.[25]

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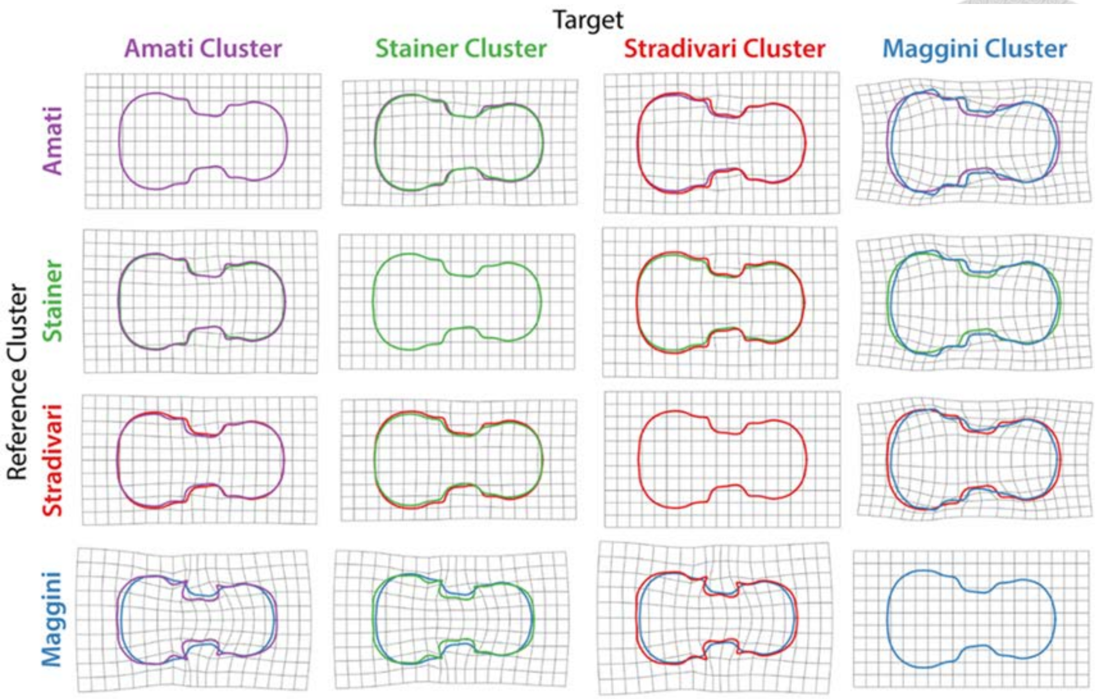

Figure 1- 12. Thin plate splines of major violin clusters.

Thin plate splines, deforming grids to transform violins from members of reference clusters (vertical) with those of targets (horizontal), are provided.[25]

On the other hand, Alam tried to connect the structure evolution to the acoustic evolution. After measuring the f-holes of 470 Cremonese violins, he found that the elongation of the f-hole length was correspondent to enhanced radiated power for the air resonance (Figure 1- 13).[26] Interestingly, the violins made by Stradivari have both longer f-holes and stronger air resonance than the violins made by Amati.

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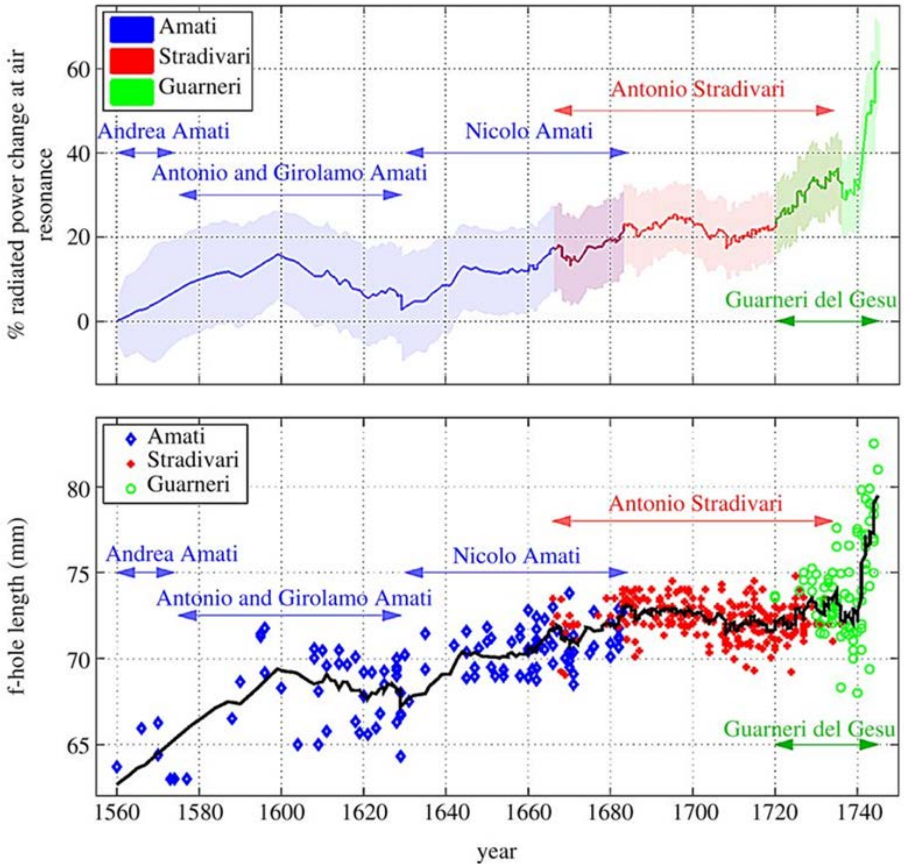

Figure 1- 13. Time series of changes in radiated power and f-hole length.

The upper: The solid line is the total radiated acoustic air-resonance power. Colored shaded patches represents the standard deviations. The lower: The colored markers are the f-holes measured from 470 Cremonese violins. The black line represents 10-instrument running average.[26]

However, the acoustic evolution is still not clear and there are still many unanswered questions. Some of the important questions are why the sound of some violins are better than the others, and why many soloists prefer to play Stradivari violins. The answers are hard to be found because the frequency response of the different violins often look similar to one another. It made us start to think of how to use other methods to analyze the frequency response and resonance properties, how to see all the peaks Bissinger suggested in a single experiment, and how to simulate the perception in our mind when we hear certain resonance features.

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1.5. The acoustics of vocals in comparison with violins

There was an old notion that the violin could sing. Francesco Geminiani, a famous Italian violinist from the Baroque period, stated that the ideal violin tone should “rival the most perfect human voice” in 1751.[27]

In most cases, the vocal range of all the males is from E2 to A4 and all the females is from F3 to C6. The organs and the tissues used to produce voice could be seen in Figure 1- 14.[28] In the larynx, the muscles controlled by the vagus nerve adjust the tension of the vocal folds and the opening of the glottis, influencing the fundamental frequency. To oscillate, the vocal folds are brought near enough together, so the air pressure builds up beneath the larynx. The folds are then pushed apart by this increased subglottal pressure.[29] It causes an energy transfer from the airflow to the fold tissues. Under the right condition, the energy transferred to the folds is large enough to overcome losses by dissipation and the oscillation pattern would sustain itself.[30]

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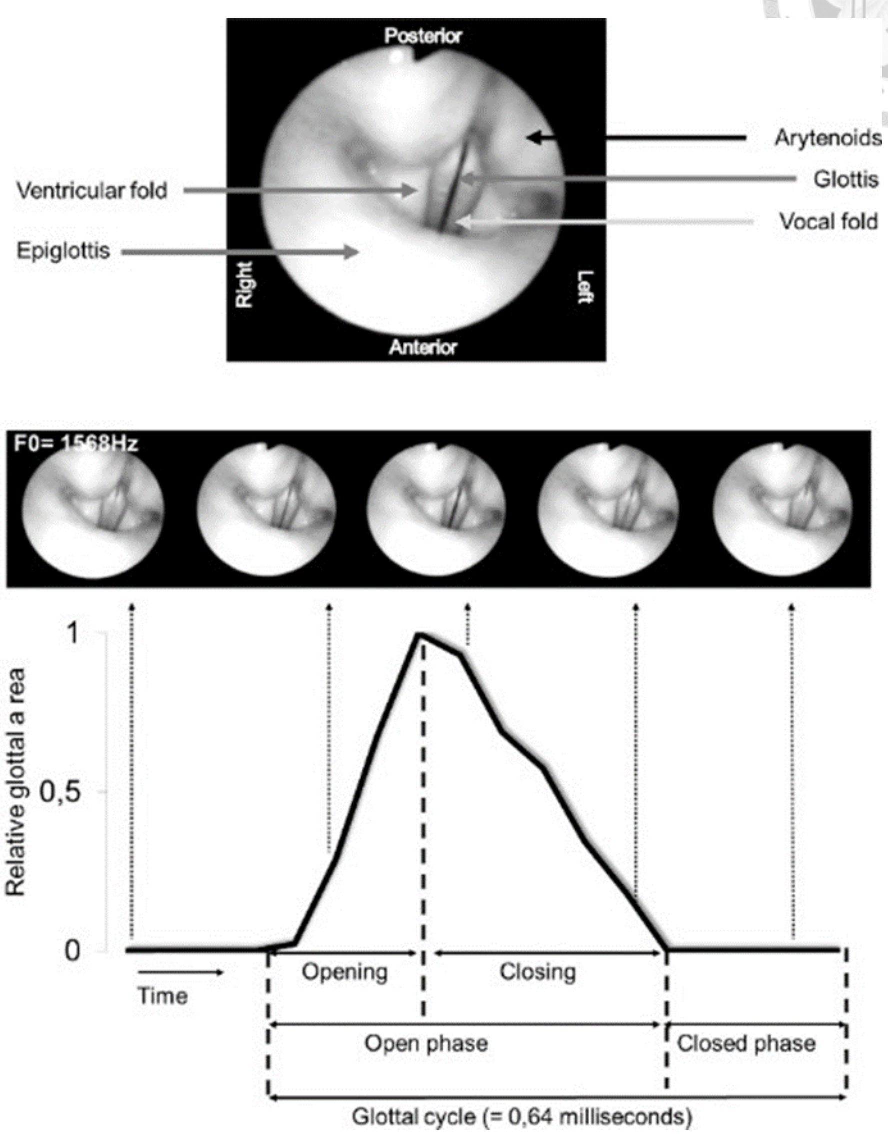

Figure 1- 14. Representative images of the vocal fold vibration.

The pictures refer to the voice production of soprano at a fundamental frequency of G6 (1568 Hz). The laryngoscopic view represents one glottal cycle in relation to a glottal area waveform.[28]

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After the glottal excitation, the oscillated airflow composed of the fundamental and related harmonic frequencies goes from the glottis to the vocal tract. The vocal tract has the similar function to the violin bridge and chamber. Because of the length, size and shape, the tract would enhance or weaken the intensity of several specific frequency bands, and it causes the certain peaks in the frequency response called the formants. The shorter larynx and vocal tract of females cause the higher fundamental frequency and formants than males.[31-33] The size and the shape of tract are influenced by the tongue position.[34] Passing through the tract, the air flow is modified by the lip and the human voice can be heard of. All the processes involved in voice production can be seen in Figure 1- 15.[35] This phenomenon can be explained by the source-filter theory, which is similar to the sound production of the violin.[36-37]

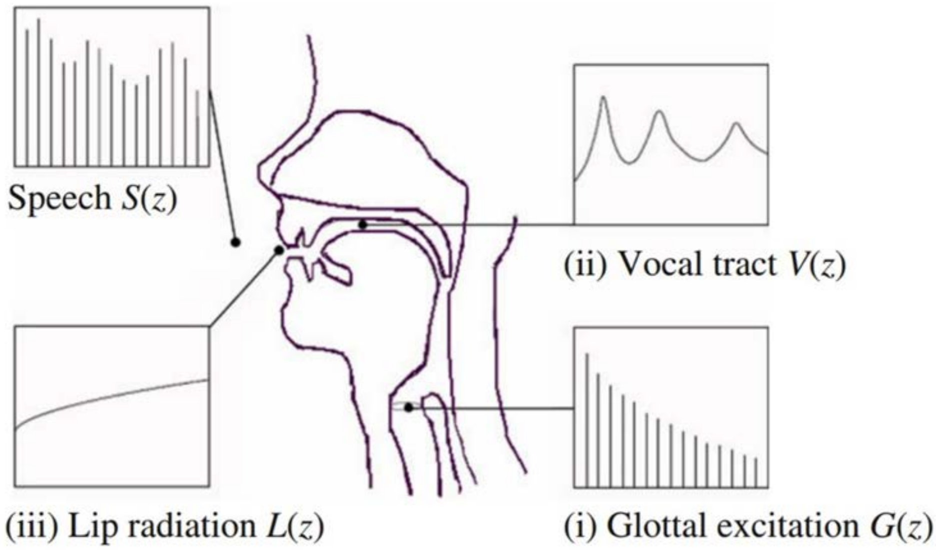

Figure 1- 15. Schematic diagram describing the production of vocal.
This figure is adopted from Alku et al., 2011.[35]

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The formant frequencies of English vowels have been studied by Childers in 1991 (Table 1- 1)[38] and Hillenbrand in 1995 (Table 1- 2)[39]. Below 5000 Hz, there are four formants in the frequency response of vocals.

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 1- 1 The formants of 10 basic vowels in English from Childers.

		/i/	/ɪ/	/e/	/ɛ/	/æ/	/ɑ/	/ɔ/	/o/	/ʊ/	/u/	/ʌ/	/ɝ/
Dur	**M**	243	192	267	189	278	267	283	265	192	237	188	263
	W	306	237	320	254	332	323	353	326	249	303	226	321
	C	297	248	314	235	322	311	319	310	247	278	234	307
***F*0**	**M**	138	135	129	127	123	123	121	129	133	143	133	130
	W	227	224	219	214	215	215	210	217	230	235	218	217
	C	246	241	237	230	228	229	225	236	243	249	236	237
***F*1**	**M**	342	427	476	580	588	768	652	497	469	378	623	474
	W	437	483	536	731	669	936	781	555	519	459	753	523
	C	452	511	564	749	717	1002	803	597	568	494	749	586
***F*2**	**M**	2322	2034	2089	1799	1952	1333	997	910	1122	997	1200	1379
	W	2761	2365	2530	2058	2349	1551	1136	1035	1225	1105	1426	1588
	C	3081	2552	2656	2267	2501	1688	1210	1137	1490	1345	1546	1719
***F*3**	**M**	3000	2684	2691	2605	2601	2522	2538	2459	2434	2343	2550	1710
	W	3372	3053	3047	2979	2972	2815	2824	2828	2827	2735	2933	1929
	C	3702	3403	3323	3310	3289	2950	2982	2987	3072	2988	3145	2143
***F*4**	**M**	3657	3618	3649	3677	3624	3687	3486	3384	3400	3357	3557	3334
	W	4352	4334	4319	4294	4290	4299	3923	3927	4052	4115	4092	3914
	C	4572	4575	4422	4671	4409	4307	3919	4167	4328	4276	4320	3788

Table 1- 2 The formants of 12 basic vowels in English from Hillenbrand.

M: males. W: females. C: children.

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Among the different vowels, the main differences lie in the first and the second formant (F1 and F2). Connecting these vowels to International Phonetic Alphabet (IPA) vowel chart (Figure 1- 16), we can see the relation between the formant and the tongue position. The lower the tongue, the higher F1. The more forward the tongue, the higher F2. The third and the fourth formant (F3 and F4) are almost the same except for the rhotacized vowel.

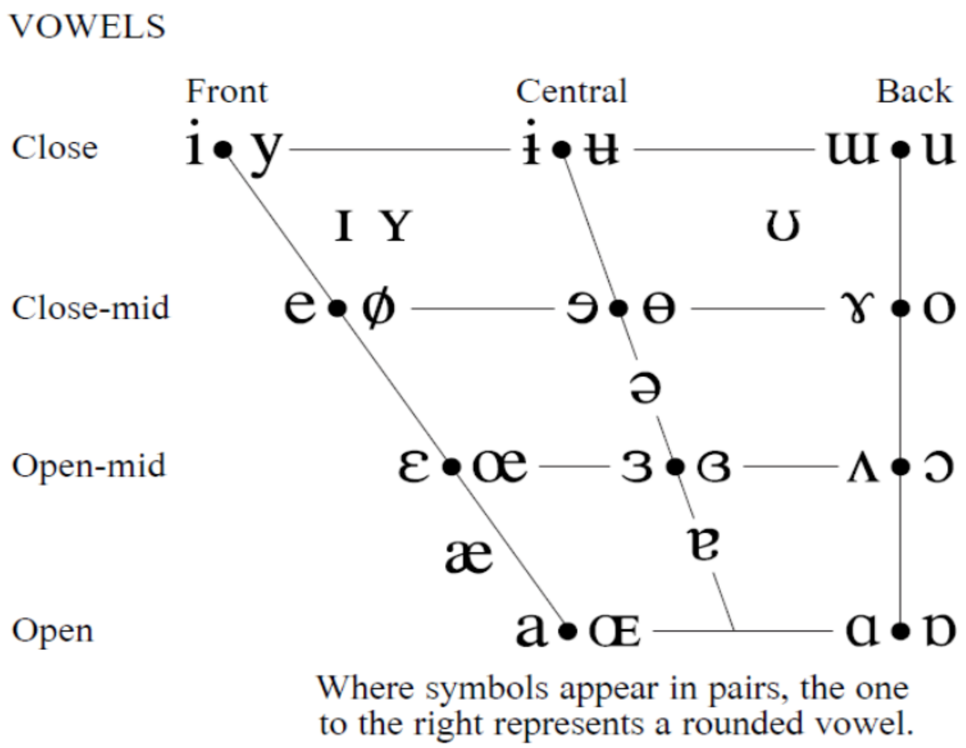

Figure 1- 16. The IPA vowel chart.

<https://www.internationalphoneticassociation.org/sites/default/files/IPA_Kiel_2015.pdf>

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F1 and F2 of females are a little higher than males, but the formants vary greatly with different vowels. F3 and F4 were significantly higher than males. Moreover, the formants of children are more like females. To sum up, F1 and F2 are mostly determined by vowels, and F3 and F4 are mostly determined by genders.

In 2012, our group used linear predictive coding method (LPC), a common speech analysis technique, to analyze the sound of violins, finding four formants in violins (Figure 1- 17).[40] However, recalling Figure 1- 6 that Bissinger proposed, there are five peaks in the frequency response of violins. Comparing the two researches, all the four formants found by LPC method correspond to the peaks Bissinger proposed. Only A0 mode, the air resonance peak, doesn't appear in the LPC formant analysis. Hence, LPC analysis is able to identify four violin formants that resemble voice formants. After our study, a similar result of LPC method was published by Nagyvary. He also applied a speech analysis method to map the first and the second violin formants to the IPA vowel chart (Figure 1- 18),[41] connecting the violin sounds to the vocals impressively.

Recently, followed by Nagyvary, Mores modified the LPC formant analysis and compare the different violins in the aspect of vowel chart. He found that either Guarneri del Gesù or Antonio Stradivari has his own formant features in the coordinate system related to the vowel chart (Figure 1- 19).[42] This research shows that the violins made

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by Stradivari show the quality of front vowels. It also shows that the violins present similarities from the same maker, and present differences from the different makers.

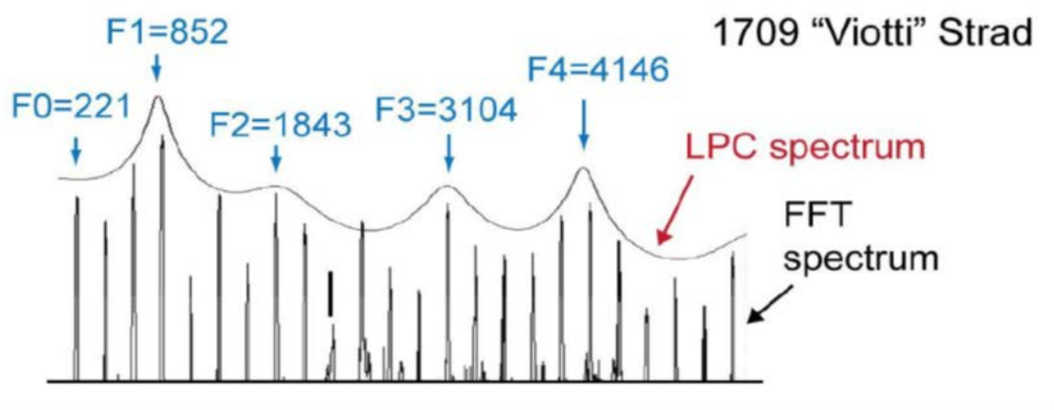

Figure 1- 17. The formants of Viotti Strad violin analyzed by LPC method.

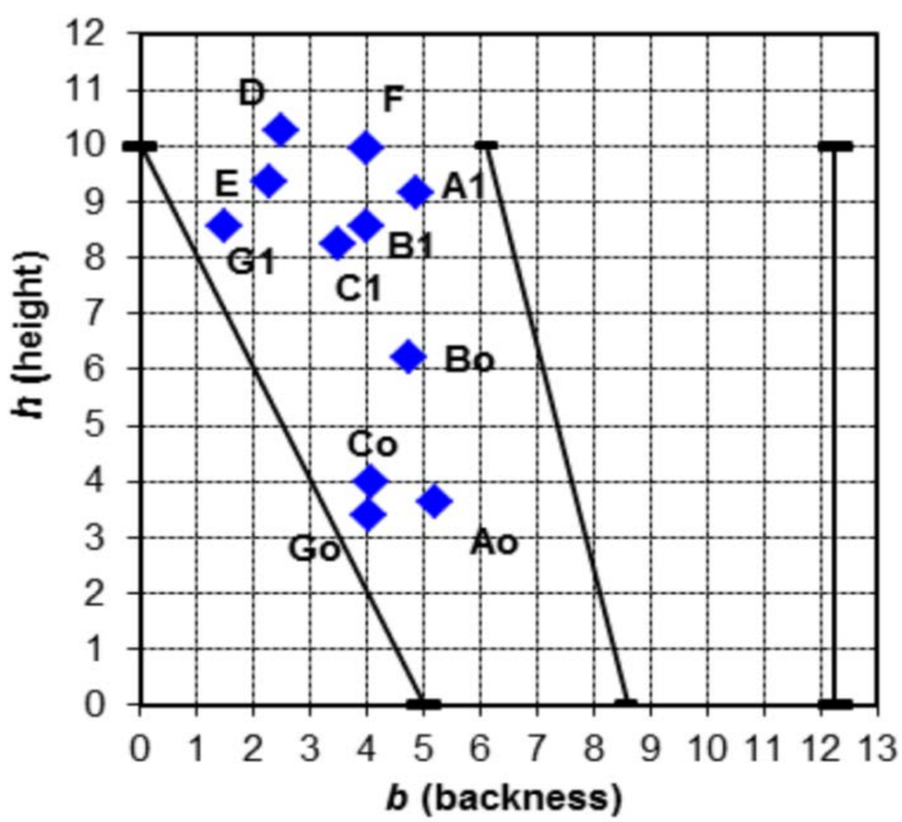

Figure 1- 18. The notes of "Ole Bull" Guarneri violin in the vowel chart.

The suffix 0 designates the notes on the G string.

The suffix 1 indicates the higher octave.[41]

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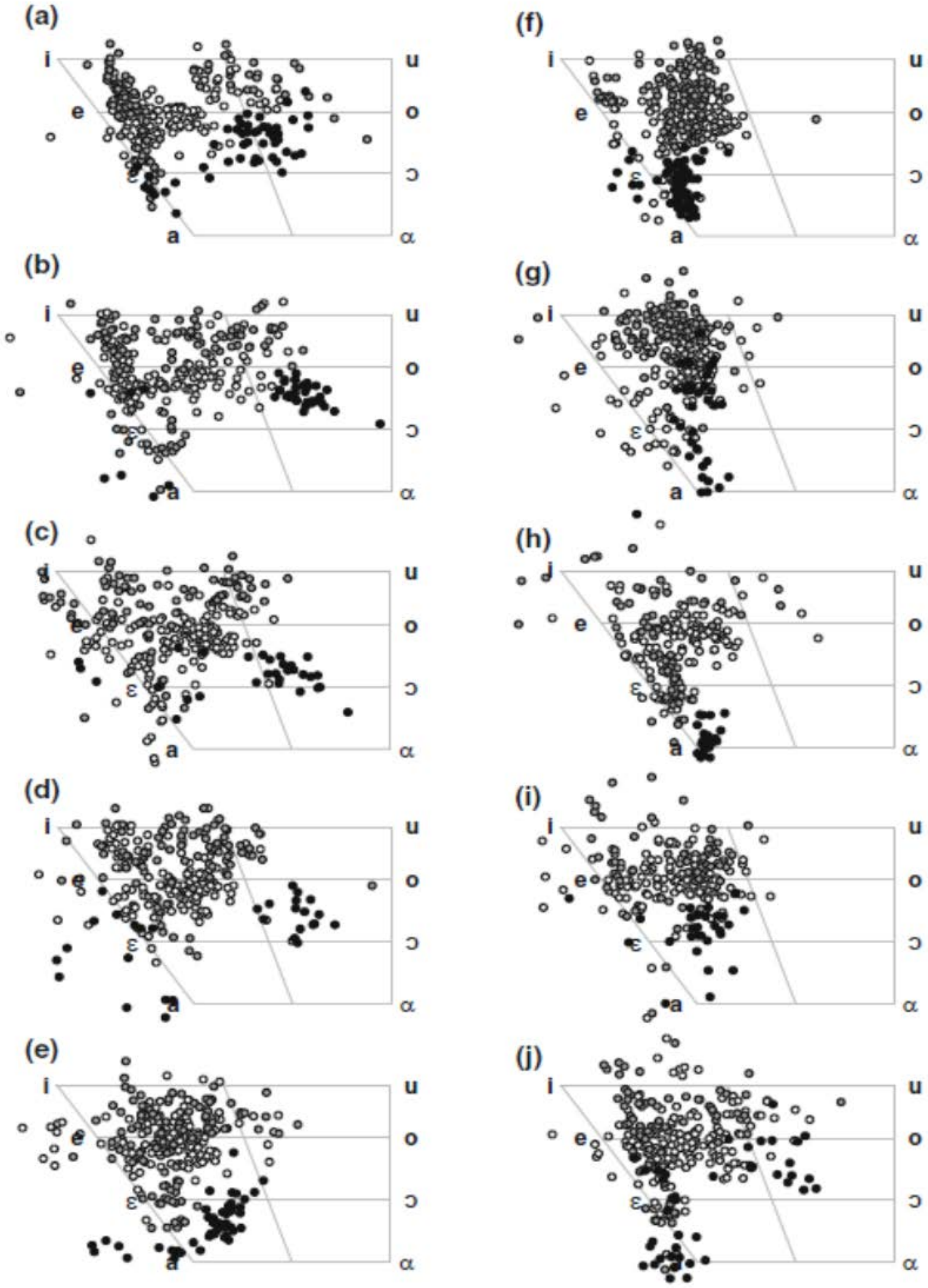

Figure 1- 19. Vowel quality of Guarneri del Gesù and Stradivari violins.
(a-e) Guarneri del Gesù violins. (f-j) Stradivari violins. Black circles played between G3 and C#4, gray circles played between D4 and G#4, white circles played A4 or above.[42]

Based on these prior works, the acoustic methods of comparing violins to vocals have been created and developed. It gives us some clues to finding the secrets in the origin and evolution of violin acoustics.

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1.6. Rationale and research aim

Our group want to prove the old notion that the violins are related to "the most perfect human voice". We aim to use formant analysis to compare the violin acoustic to vocals. However, in previous literatures, the formants of the vowels were recorded in speech, not singing. This made it difficult to compare the violin formants to the vocals. Hence, we recorded the different vowels in singing. We recorded the notes of both violins and vocals from G#3 to G4 because both males and females can sing in this pitch range which is correspondent to the lowest octave of violins without special training. Within the same pitch range, we aim to compare the violins to the vocals by formant analysis.

To know how the process that the luthiers tried to pursue "the most perfect human voice", we aim to analyze the evolution of the violin formants. Over the past 500 years, there were two widely recognized acoustic landmarks. The first landmark was the invention of the modern violin in the early 16th century by Amati, and we recorded the 1570 Andrea Amati and 1560 Gasparo da Salo to analyze the origin modern violin. The second landmark was achieved by Antonio Stradivari in the early 18th century, who made some modifications to improve the violin acoustics, and we recorded 6 violins made by Stradivari family to analyze the violin features in this period. Besides, we recorded the other 7 violins which were made between the time of the two landmarks. By analyzing these 15 violins, we aim to know how the formant evolution is.

In the last part of this research, we discuss the related researches to deduce how the luthiers tune the violin formants by changing construction design and material chemistry, and try to know how the luthiers achieve the formant evolution.

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Chapter 2 Experiment Methods

2.1. Sound Recording

2.1.1. Violin recordings

We recorded the scales of 15 old Italian violins (Table 2- 1) during a one-day session at the recital hall of the old Chi Mei Museum (Tainan, Taiwan) in November, 2011. All instruments were generously loaned by the Chi Mei Museum and set up by Dai-Ting Chung. Violinist Chu-Hsuan Feng, a graduated of the Paris Conservatory, used a French bow by Jean Pierre Marie Persoit to play the chromatic scale. Each note in the scale was played twice consecutively with down bows (~1.5 s) at forte loudness without vibrato. The fingering chart is showed in Figure 2- 1. The violinist was informed about the maker before recording each instrument, and was asked to maintain a consistent bowing style while playing different violins.

The old Italian violins	The Stradivari violins
Andrea Amati 1570	Stradivari 'Dubois' 1667
Gasparo da Salo 1560	Stradivari 'Dushkin' 1707
Paolo Maggini 1610	Stradivari 'Viotti' 1709
Nicola Amati 1624	Stradivari 'Wirth' 1713
Nicola Amati 1656	Stradivari 'Elman' 1722
Francesco Ruggeri 1694	Omobono Stradivari 1740
Giuseppe Guarneri *filius Andrea* 1706	
Giuseppe Guarneri *del Gesù* 'Lafont' 1733	
Carlos Bergonzi 1732	

Table 2- 1. 15 old Italian violins we recorded.

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Three stereo pairs of microphones were set up on the stage to record the violin from different angles (Figure 2- 2). Channels 1&2: Avenson STO-2 electret condenser omnidirectional microphones, in spaced configuration (80 cm apart). Channels 3&4: Neumann U87 large-diaphragm condenser microphones with cardioid setting, in ORTF configuration (110°/17 cm). Channels 5&6: Oktava MK-012 with electronics modifications by Michael Joly, equipped with small-diaphragm cardioid condenser capsules, in ORTF configuration (110°/17 cm). The microphone preamplifier was a Sytek MPX-4A for channels 1-4, connected to a Tascam DR-680 digital recorder. The pre-amplifier/recorder for channels 5&6 was a Tascam HD-P2, with electronics modifications by Oade Brothers. All channels were digitally recorded at 24 bit/96 kHz into uncompressed wav files.

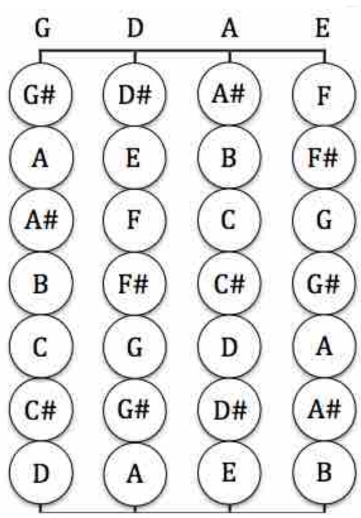

Figure 2- 1. Violin fingering chart.

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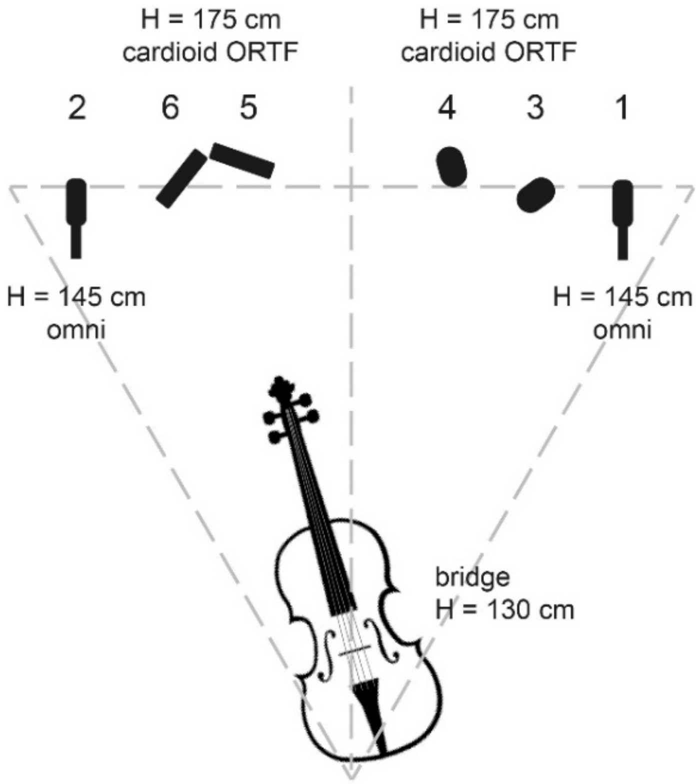

Figure 2- 2. The top view of microphone recording setups.

Three stereo microphone pairs were set up in spaced omni-directional (channels 1&2) or Office de Radiodiffusion Television Francaise (ORTF) configurations (channels 3&4, 5&6). Each microphone was horizontally ~70 cm from the violin bridge, with their heights from the stage floor labeled respectively. All dashed grey lines represent 1 meter.

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2.1.2. Vocal recordings

We recorded the scales sung by 16 subjects, including 8 males and 8 females. Their ages ranged from 16 to 30. They all volunteered to participate in this research, and all had more than 3 years of music experience in an amateur chorus or an amateur orchestra. Every subject was asked to read a list containing 8 words, including “had, head, heard, heed, hod, hoed, hud, who’d”. The vowels in these words were associated with the symbols “/æ, ɛ, ɝ, i, ɑ, o, ʌ, u/” in International Phonetic Alphabet. Subsequently, the subjects used their natural voice to sing the chromatic scale (G#3-G4) for each word. This octave range was chosen because it could be comfortably sung by both male and female subjects. Before singing each note in the scale, the subjects were made to hear the sound of the piano which was recorded in advance to ensure they could sing in the right pitch. In the recording, each note in the scale was sung for 1.0-1.5 sec and was sung twice consecutively.

An MXL USB.007 stereo cardioid microphone (Segundo, CA), equipped with two gold diaphragm capsules in X-Y pattern, was placed 20 cm in front of the subject to make 16 bit/44.1 kHz stereo recordings into uncompressed wav files, recorded by Audacity software (version 2.1.2).

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2.2. Analytical Methods

2.2.1. Frequency response analysis

We imported the violin recordings into Audacity to analyze the frequency response of each violin and the differences between the Stradivari and the non-Stradivari violins. In the tool bar of Audacity, there was a built-in function, “Plot Spectrum”, in the column of “Analyze” (Figure 2- 3). We used this function to run the fast Fourier transform(FFT) and analyzed the lowest octave which was from G#3 to G4 in each violin. After clicking in the “Plot Spectrum”, we went into the interface of “Frequency Analysis” (Figure 2-4). In this interface, there were some parameters that have to be set. We set the algorithm to the spectrum, set the function to Hamming window and set the axis to the log frequency. In the analysis of the first formant, the size was set to 2048 (resolution: 46.875 Hz) and the first formant was defined as the strongest frequency between 400 and 900 Hz. In the analysis of the second formant, the size was set to 512 (resolution: 187.5 Hz) and the second formant was defined as the strongest frequency between 900 and 2800 Hz. We could easily define the strongest frequency as the formant because the software could automatically assign each peak. Then, we exported the data to do the further analysis.

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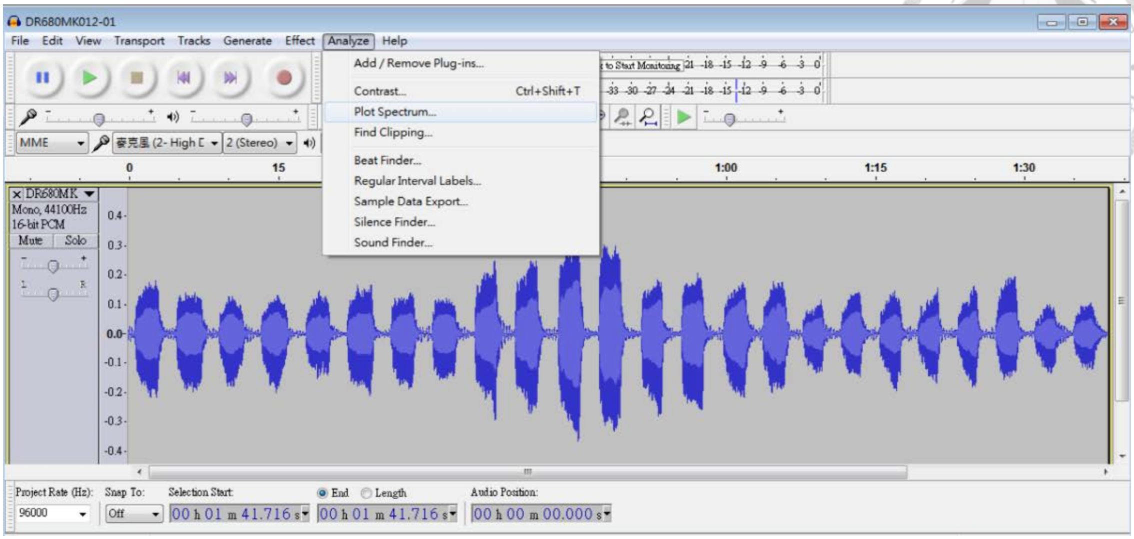

Figure 2- 3. The interface and the tool bar of Audacity.

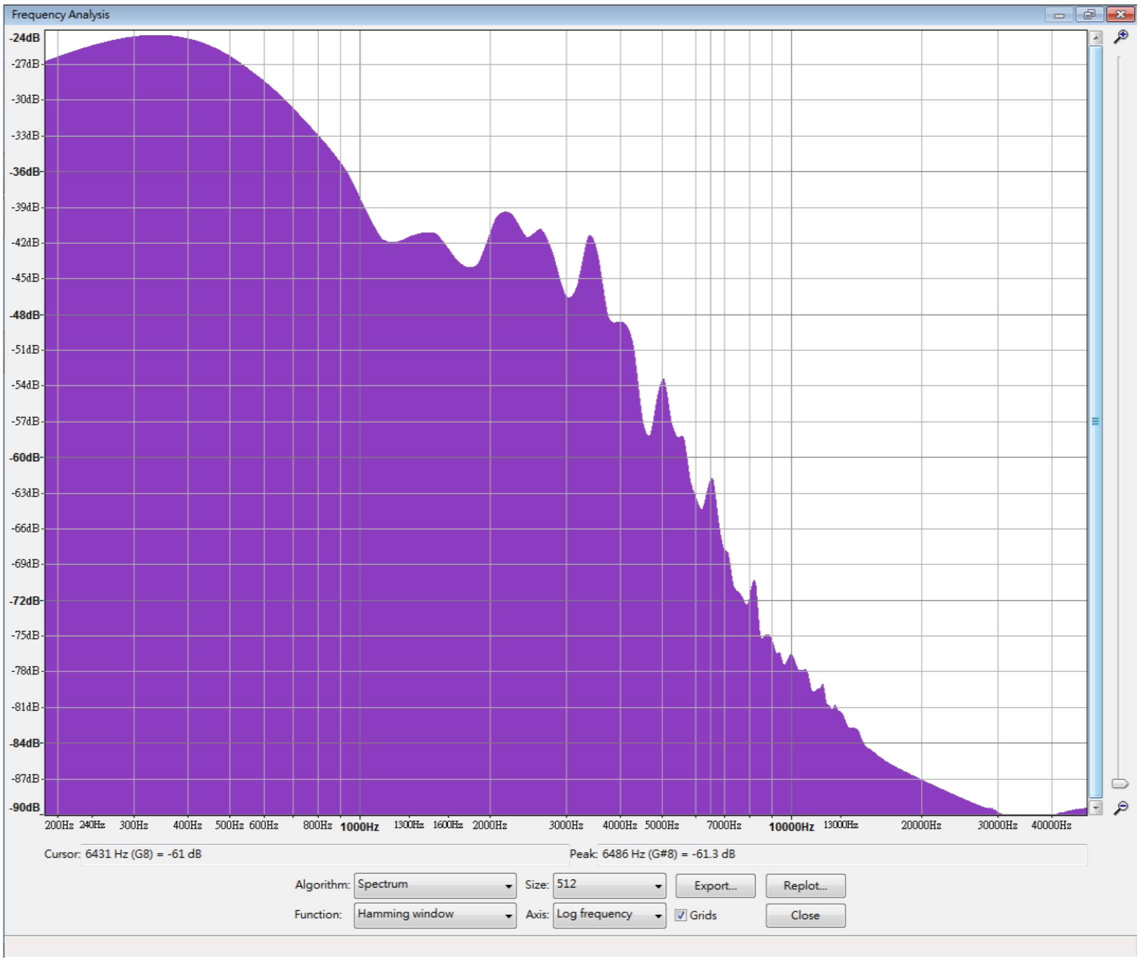

Figure 2- 4. The interface and the parameters in "Plot Spectrum".

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We aimed to analyze the difference between the Stradivari and the non-Stradivari violins, so we were interested in analyzing the frequency response of the two groups respectively. To normalize each frequency response spectrum, the highest point was set as 0 dB. The normalized values were exported and connected using the spline method. We chose this method because we could get the same results as Audacity when finding the formants of each violin. In this way, we obtained the frequency response of the Stradivari and the non-Stradivari violin groups.

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2.2.2. Formants analysis

Praat is a free software that many researchers use to study human voice. By Praat, we used the LPC method to identify the formants of vocal and violin recording.

In the voice analysis, we selected a steady-state period of 0.1 sec for each note, and the formants were computed for this period (Figure 2- 5). Spectrogram, pitch and formant setting were also important parameters. In spectrogram setting, we used Fourier method and Hamming window (raised sine-squared) with 0.02 sec time window length. We set the number of time steps to 1000, the number of frequency steps to 250, the maximum to 100 dB/Hz, pre-emphasis to 6 dB/oct, and dynamic compression to 0. The view range was from 50 to 5500 Hz and the dynamic range was 50 dB. In the pitch setting, we used the autocorrelation method and the range was from 50 to 5500 Hz. We set the maximum number of candidates to 15, the silence threshold to 0.03, the voicing threshold to 0.45, the octave cost to 0.01, octave-jump cost to 0.35 and voiced/unvoiced cost to 0.14. The drawing method was automatic and the view range was from 50 to 5500 Hz. In formant setting, we used Burg method, and set pre-emphasis from 50 Hz. We set the maximum formant to 5500 Hz, the number of formants to 5, the window length to 0.02 sec, the dynamic range to 70 dB, and dot size to 1 mm. According to these settings, we obtained the first to fourth formants of all sung vowels.

In the violin analysis, we also selected a steady-state period of 0.1 sec for each

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note. Most of the parameters were the same as vocal analysis, except for the pre-emphasis in the formant setting. We changed the pre-emphasis to 10000 Hz to avoid interference because violins can project strongly into 7-8 kHz range. After obtaining the formants from each note, we averaged the formants which were over the same pitch and the same violin in the six microphones. According to this procedure, we obtained the first to fourth formants of all the violins that could be compared to the vocals.

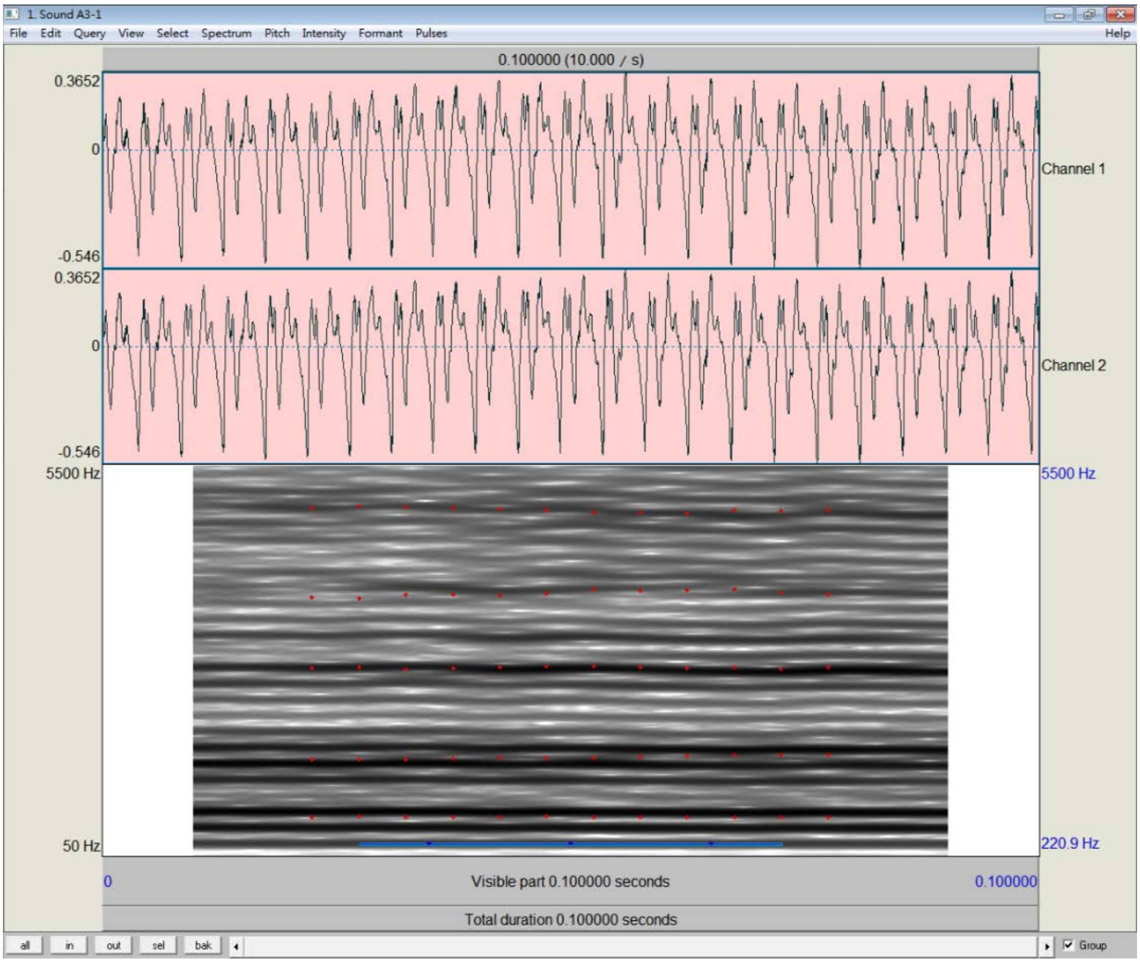

Figure 2- 5. The example of the formant analysis of vocals in Praat.

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2.2.3. Formants to vowel diagram mapping

To convert our formant data to IPA vowel chart, we used the method which Pfitzinger developed.[43] He measured the pitch (F0), the first formant (F1) and the second formant (F2) values from the individual vowels. He transformed these values to an x-y coordinate system where x value was defined as backness (b) and y value was defined as height (h) by the two empirically derived equations shown below:

$$b = 1.782 \times \ln(F_1) - 8.617 \times \ln(F_2) + 58.29 \quad (\mathbf{1})$$

$$h = 3.122 \times \ln(F_0) - 8.841 \times \ln(F_1) + 44.16 \quad (\mathbf{2})$$

By these two equations, we transformed our vocal data into coordinates which resemble the IPA vowel chart (Figure 2- 6). In our violin data, after obtaining the backness and height for each note, we averaged the backness and height which were at the same pitch and the same violin over the six microphones as before. Hence, we could connect the violin sounds to the vocals in the aspect of vowel chart.

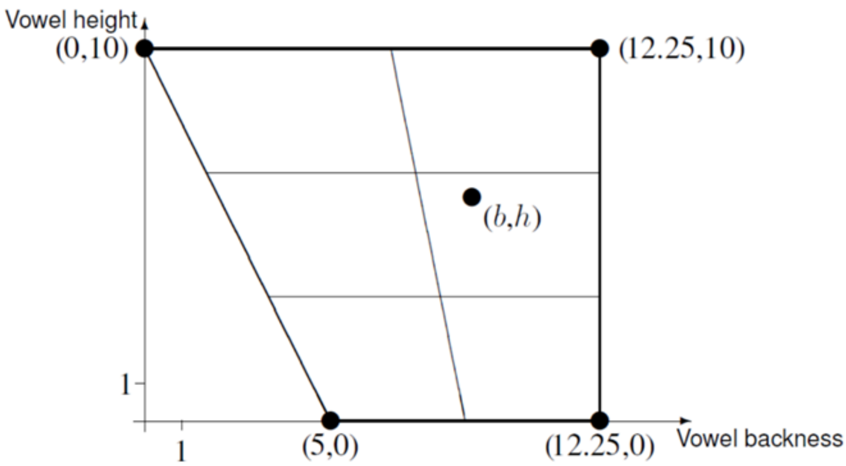

Figure 2- 6. Dimensions of the Vowel chart developed by Pfitzinger.

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Chapter 3 Results

3.1. The acoustic features of the origin violins

3.1.1. Frequency response

To compare the violin and the vocal, we record the singing voice by ourselves. Then, we use FFT methods to check the quality of our records. G4 is the most difficult to sing for males in our notes because of the high pitch. Hence, we choose this pitch as our example of the frequency response curves. In all the 16 curves in Figure 3- 1, the fundamental frequencies are all in around 392 Hz, corresponding to G4, and all the harmonic frequencies are the multiple of 392 Hz. It proves that the quality of our records is good enough to do the following analysis.

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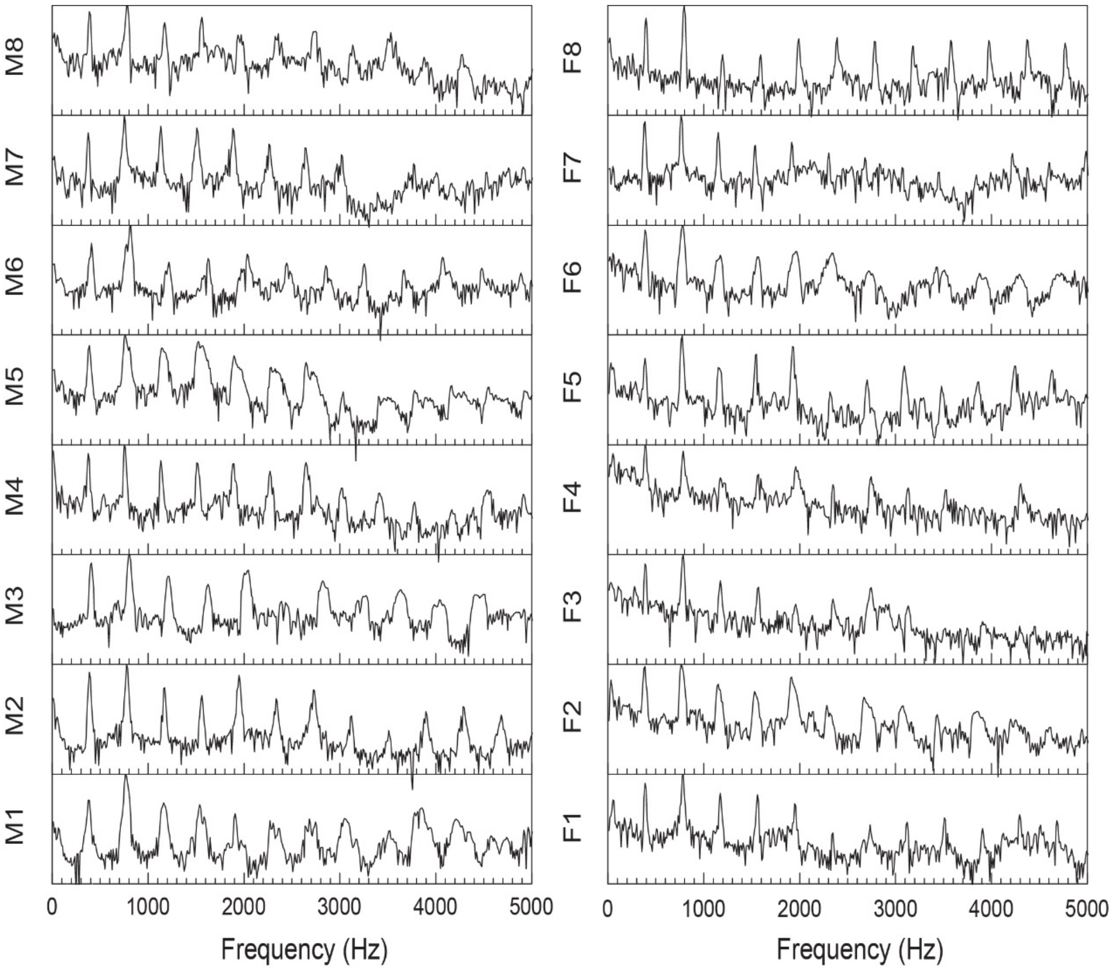

Figure 3- 1. The example of the frequency response curves of singing.

The curves acquired from the 8 males are in the left column, and the curves acquired from the 8 females are in the right column. All the people were asked to sing [ɛ], and all the musical note is G4.

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Just like the singing voices, we use FFT methods to analyze the frequency response of the Amati 1570 and the da Salo, which represent the earliest modern violins in our experiment. Afterward, we try to directly acquire the formants from the frequency response curves because the formants are some of the most important features that people use to judge the voice. In Figure 3- 2, it shows the example of how we define the F1 and the F2. These curves are acquired from the chromatic scales from G#3 to G4. We find the F1 in the resolution of 46.875 Hz to observe the formant more clearly below 1000 Hz. On the other hand, we find the F2 in the resolution of 187.5 Hz to define the formant more easily in the range from 1000 to 3000 Hz. After averaging the 12 notes (6 microphones × 2 times), the F1 and the F2 of Amati is 551 and 1551 Hz, and the F1 and the F2 of da Salo is 574 and 2214 Hz. However, we find that the intensities of the different peaks are close to one another, and it is hard to define the formant, especially the F3 and the F4. Moreover, when the violin is played, we listened to it in one note at a time. The rationality of analyzing an averaged octave signal should be questioned. Therefore, we use the LPC method to analyze the formants of the two violins note by note in the following experiments.

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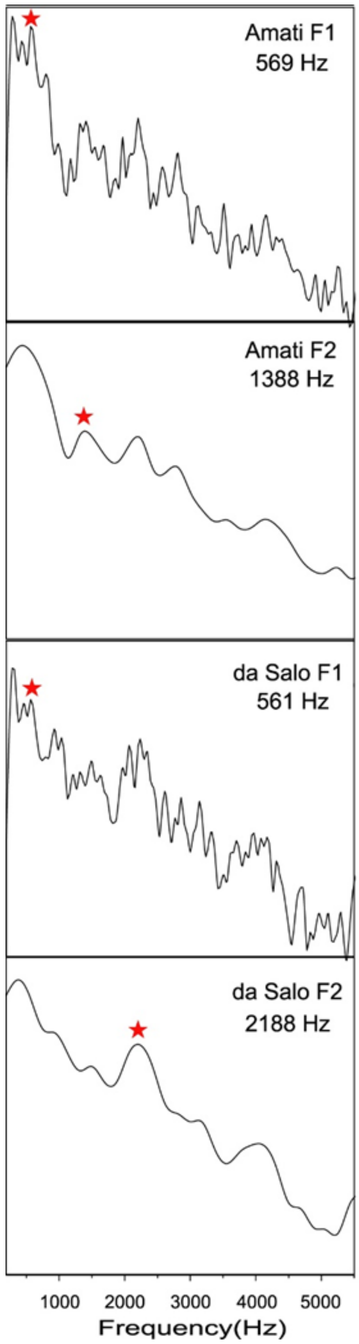

Figure 3- 2. The example of how to define the formant of violins from the frequency response. The frequency response curves are acquired from the chromatic scales from G#3 to G4. The F1 is found in the resolution of 46.875 Hz. The F2 is found in the resolution of 187.5 Hz. The star is the peak that is defined as the formant.

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3.1.2. Similarities with vocals

The LPC method is used to analyze the formants of both the vocals and violins. In the bottom half of Figure 3- 3, we show two sets of harmonic series of notes sung by a male and a female. The amplitude of the two series decrease with rising frequency. Among the series, some of the frequency bands are attenuated by the vocal tract, causing the formants. Using the LPC method, we obtain two smooth curves above the two harmonic series, and we can easily define the position of the first four formant peaks.

In the top half of Figure 3- 3, there are two sets of harmonic series of violins, the 1570 Amati and 1560 Gasparo da Salo. Interestingly, the shape of the two smooth curves obtained by LPC method is similar to the vocal curves. The most important feature is the fact that all the four formant frequencies are close to these of the vocals.

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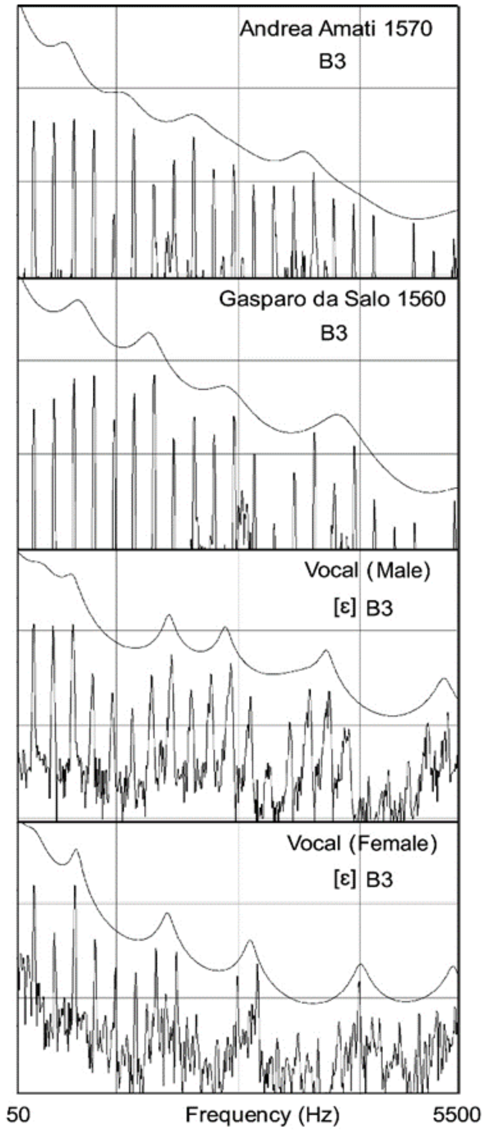

Figure 3- 3. The illustration of the LPC method on vocals and violins.

The musical note is B3. In each frame, there are one sets of harmonic series acquired by the FFT method and one smooth curve acquired by the LPC method.

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We find that musical note has limited influence on the frequency of the formants. In Table 3- 1, each formant of the vocals is the average of the 192 notes (8 people × 12 musical notes × 2 times). Considering all vowels, the frequency of F1 is from 418 to 803 Hz, F2 is from 995 to 2298 Hz, F3 is from 2207 to 3034 Hz and F4 is from 3501 to 4290 Hz. On the other hand, each formant of the violins is the average of the 144 notes (6 microphones × 12 musical notes × 2 times), and all the averages are in the frequency range of the corresponding vocal formant.

Example		had	head	heard	heed	hod	hoed	hud	who'd	Avg.	Amati	daSalo
IPA		æ	ε	ɝ	i	a	o	ʌ	u			
F1	male	776	658	634	464	790	666	732	497	652	503	497
	female	754	676	666	418	803	559	756	423	632		
F2	male	1641	1794	1407	2116	1232	1068	1270	995	1440	1583	1509
	female	1862	2019	1502	2298	1335	1078	1380	1098	1571		
F3	male	2647	2626	2207	2772	2787	2877	2773	2769	2682	2602	2515
	female	2918	2964	2247	3034	3021	2908	3008	2756	2857		
F4	male	3805	3845	3501	3752	3748	3749	3813	3748	3745	3731	3594
	female	4239	4290	3850	4165	4144	4026	4183	3951	4106		

Table 3- 1. The formants of the Amati and the da Salo comparisons with vocals.

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3.1.3. Vowel qualities

Studies have previously shown that humans produce different vowels mainly by altering F1 and F2 frequencies with different mouth shapes and tongue positions. Besides, both F1 and F2 are affected by F0 in speech and singing.[44] To analyze the recorded sung vowels, we converted them to the IPA vowel chart by Pfitzinger's method. In the equation (**1**) and (**2**), F1 is the main influence on the vowel height and F2 is the main influence on the vowel backness. After the transition, all the sung vowels correspond correctly to the IPA vowel chart (Figure 3- 4 b). Although [ʌ] and [ɑ] are a little more forward due to the deformation of the tongue position when singing, the relative relationship of all the vowels is still correct. In the same vowel, the tongue position of each person is still a little different from each other because of different pronunciation and singing habits. It causes the tongue positions to show a spread of distribution. All the values of the average and the standard deviation can be seen in Appendix- 1. Besides, after the transition, all the formants in Table 1- 1 and Table 1- 2 are also consistent to the vowel chart we recorded (Appendix- 2).

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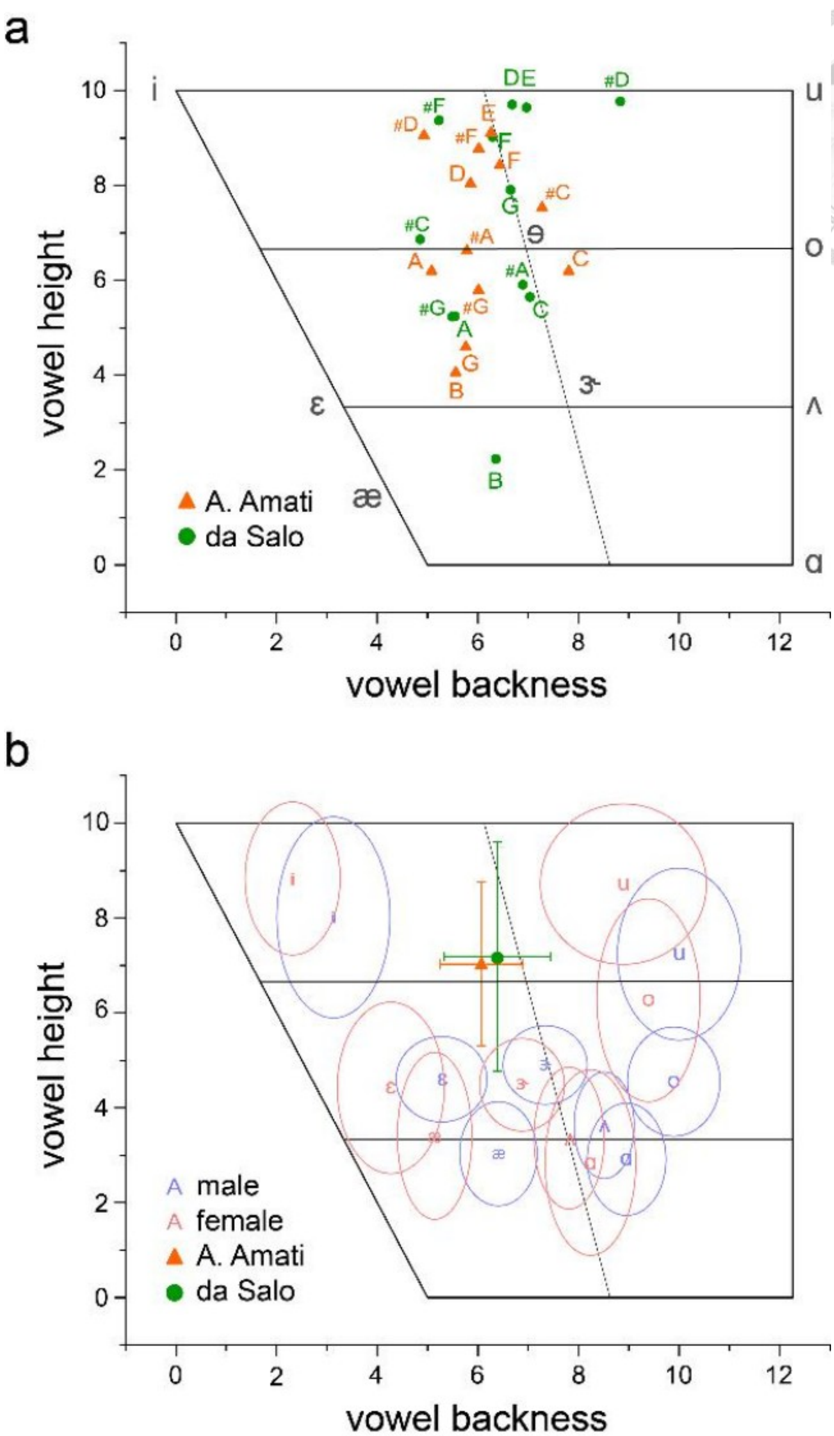

Figure 3- 4. Vowel qualities of the Amati and the da Salo.

(a) Vowel backness and height of each violin note from G#3 to G4. (b) The mean backness and height of each violin are represented by the position of the IPA vowel symbol. The centers of each ellipse are the mean backness and height of the 8 males and the 8 females we recorded. The lengths and widths of each ellipse represent the standard deviations. The average values of each violin are represented by colored shapes, and the vertical and horizontal whiskers represent the standard deviations.

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In Figure 3- 4 a, the individual violin notes are scattered over different positions, but every note falls in the region of the vowel chart (Appendix- 3). In terms of vowel backness, the notes concentrate in the central part. Both the Amati and da Salo violin show similar trends with the rising pitch. From note G to #C, the notes are all lower than 7.95 in vowel height. From note D to #F, the notes are all higher than 7.95 in vowel height. Comparison with human singing, the notes of these two violins are similar to some of the vowels. In Amati, the note B is close to [ɛ], the note C is close to [ɝ] and the note #D is close to [i]. In da Salo, the note B is close to [æ], the note C is close to [ɝ], the note #D is close to [u], the note #F is close to [i] and the note #G is close to [ɛ]. It is apparently that the sounds of the violin are similar to the different vowels in the different musical notes.

With the average values of F1 and F2 in Figure 3- 4 b, we compare the violins to the vocals. The two violins are close to each other in the vowel chart. They are in the central close-mid and corresponded to the vowel [ɘ] that we didn't record. This vowel is not used in English, and the position of the vowel is in the center of all the other vowels. Based on the analysis above, we can suggest that it is why violins are described as human singing and why no one could describe what the specific vowel the violins are like.

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3.1.4. Gender qualities

Studies show that people differentiate the gender based on F4.[38, 45] In most of case, because of the shorter vocal tract in females, F4 of females is higher than males. F3 is the clue that people use to judge what the vowel is, and in the previous research, F3 of females is still higher than males.[31, 34] To make our analysis easier and clearer, we set F3 and F4 as the two axes and plot the data we recorded onto the plane. In Figure 3- 5 a, the F3 of [ɝ] is lower than the other vowels. Excluding [ɝ], the other vowels cannot be differentiated because most of the vowels overlap to each other. In spite of that, we can divide these vowels into two group based on the gender. Both the F3 and F4 of females are higher than males. Although all our data are recorded in singing, the results (Appendix- 4) are consistent with the published data from speech measurements (Table 1- 1 and Table 1- 2).

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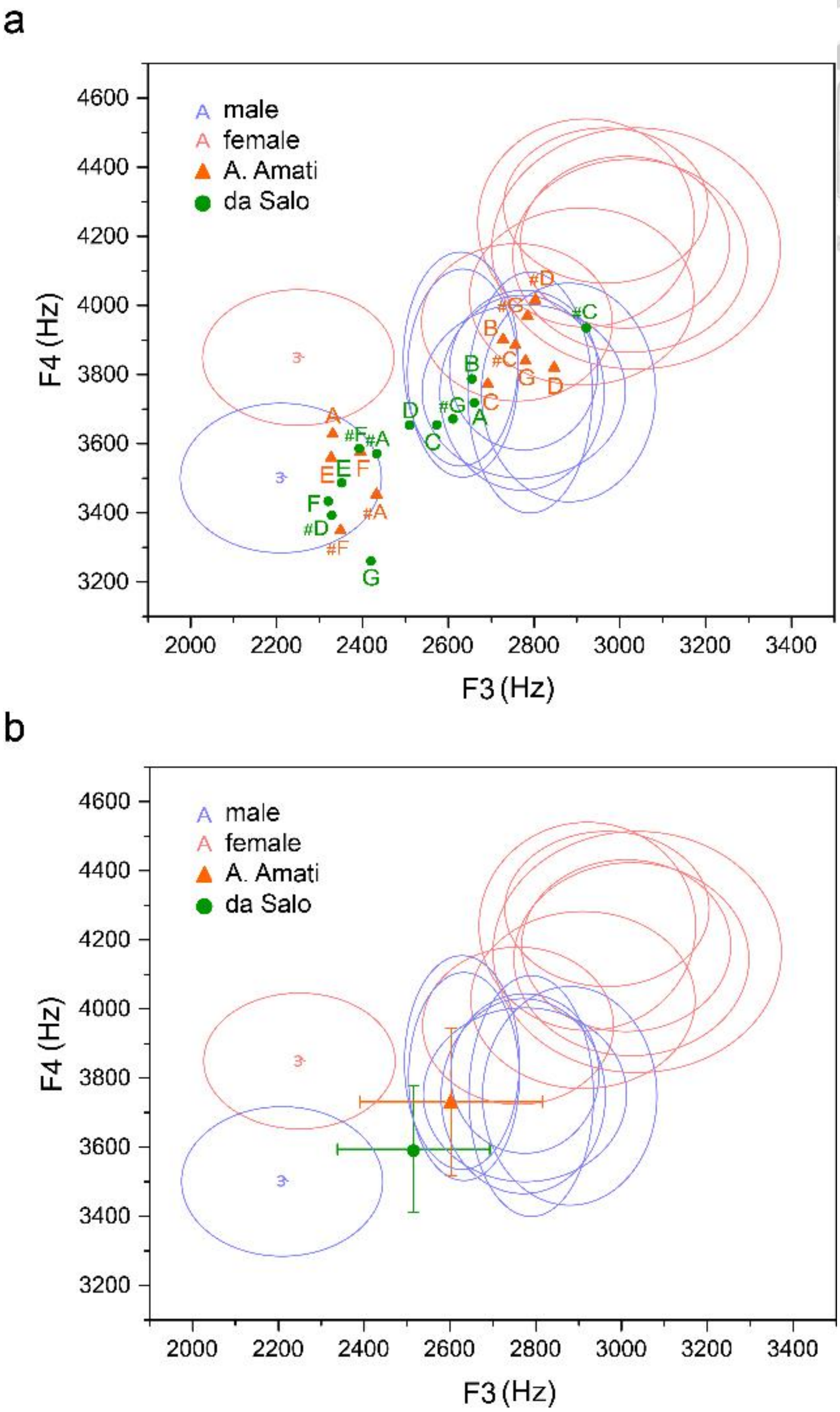

Figure 3- 5. F3 and F4 distributions of the Amati and the da Salo.

(a) F3 and F4 values of each violin note from G#3 to G4. (b) The centers of each ellipse are the mean values of the 8 males and the 8 females we recorded. The lengths and widths of each ellipse represent the standard deviations. The average values of each violin are represented by colored shapes, and the vertical and horizontal whiskers represent the standard deviations.

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In Figure 3- 5 a, the individual violin notes are scattered over different positions, and all the notes are in the region of the vocals (Appendix- 5). In F3, the notes disperse in the region from [ɝ] to the other vowels. In F4, most of the notes concentrate in the region of males and some notes are in the cross of males and females. Unlike the vowel chart, we cannot find the common trend between the two violins with the rising pitch. But, the dispersion of the two violins are different. Comparison with the human singing, half of the Amati notes is in the cross of males and females. On the other hand, most of the da Salo notes is in the region of males.

With the average values of F3 and F4 in Figure 3- 5 b, we compare the violins to the vocals. The F3 is 2602 and 2515 Hz for the Amati and the da Salo, and the F4 is 3731 and 3594 Hz. They are close to the overlapping ellipses which belong to males. Based on the analysis above, we can suggest that the Amati has some female features, although both the sound of the Amati and the da Salo are similar to the singing of males.

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To connect the sound of the violin to the gender qualities more specifically, we use the violin formants to approximate the vocal tract length (VTL). The origin of vocal formants can be explained by standing waves in a half-closed cylinder. On average, males have longer vocal tracts and therefore lower formant frequencies than females. The mathematical relationship between formant frequencies (F1 to F4) and VTL can be calculated by the following formula.[46-47]

$$\mathrm{VTL} = \left(\frac{c}{4F_1} + \frac{3c}{4F_2} + \frac{5c}{4F_3} + \frac{7c}{4F_4}\right) \div 4 \qquad (\mathbf{3})$$

(c represents the speed of sound, 343 m/s at 298K.)

Using equation (**3**), the VTL of males participating in this study is calculated to be 16.4 cm, and the VTL of females is calculated to be 15.7 cm. Compared to the anatomical VTL measurements of different voice types using X-ray images,[33] 16.4 cm is correspondent to baritones/tenors, and 15.7 cm is correspondent to altos/mezzo-sopranos. The result is in good agreement with the study about the vocal range. In the study, males that can sing from G#3 to G4 are correspondent to tenors or baritone, and females that can sing this range are correspondent to altos or mezzo-sopranos.[48]

Based on LPC analysis, the mean F1 to F4 values of the Amati are 503, 1583 ,2602 and 3731 Hz. The related VTL is 16.7 cm, corresponding to baritones. The mean F1 to F4 values of the da Salo are 497, 1509, 2525 and 3594 Hz. The related VTL is 17.4 cm, corresponding to basses. We therefore suggest that early masters in both Cremona and Brescia designed their violins to imitate male voice characteristics.

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3.2. The acoustic features of the Strad violins

3.2.1. Frequency response

Several studies have reported differences in the frequency response curves of Stradivari against other violin groups, but there are not consistent results, probably due to the different measurement methods and focus.[49-50] In our frequency response curves (Figure 3- 6), there are just a few peaks showing significant differences ($p < 0.05$). The Stradivari violins have strong formants at 2766 and 3141 Hz, and strong anti-formants at 1219 and 2344 Hz, which have also been observes by Buen.[49] Interestingly, the strong formant around 2344 Hz for non-Stradivari violins is similar to the singer's formant reported for basses.[51] In comparison, the strong formants around 2776 and 3141 Hz for Stradivari are similar to the singer's formant reported for tenors and female singers (altos/sopranos), respectively.

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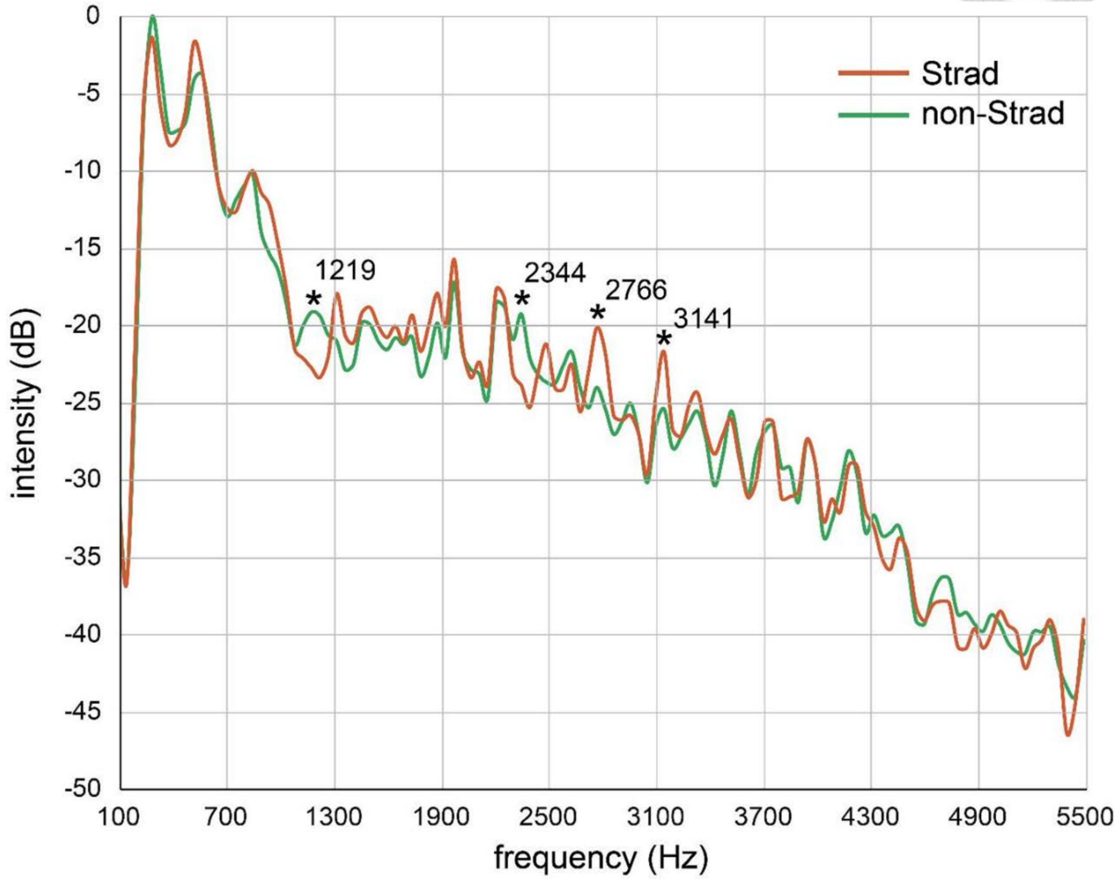

Figure 3- 6. Frequency response comparisons between Strad and non-Strad violins.

Peaks with * indicate $p < 0.05$ by two-way Welch's t-test.

n = 6 for the Strads and n = 9 for the non-Strads. The resolution is 46.875 Hz.

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3.2.2. Similarities with vocals

The LPC method is used to analyze the formants of both the vocals and violins. In Table 3- 2, each formant of the non-Stradivari is the average of the 1296 notes (6 microphones × 12 musical notes × 9 violins × 2 times), and each formant of the Stradivari is the average of the 864 notes (6 microphones × 12 musical notes × 6 violins × 2 times). All the averages are in the frequency range of the corresponding vocal formant. The amount of the data enhances the reliability that the sound of the violins can be compared to the vocals.

We find that all the formants of the Stradivari are higher than the non-Stradivari, especially F1 which is almost 10% higher. The four formants of each violin are in Appendix- 6.

Example		had	head	heard	heed	hod	hoed	hud	who'd	Avg.	Strad	non-Strad
IPA		æ	ɛ	ɝ	i	a	o	ʌ	u			
F1	male	776	658	634	464	790	666	732	497	652	554	511
	female	754	676	666	418	803	559	756	423	632		
F2	male	1641	1794	1407	2116	1232	1068	1270	995	1440	1591	1500
	female	1862	2019	1502	2298	1335	1078	1380	1098	1571		
F3	male	2647	2626	2207	2772	2787	2877	2773	2769	2682	2694	2598
	female	2918	2964	2247	3034	3021	2908	3008	2756	2857		
F4	male	3805	3845	3501	3752	3748	3749	3813	3748	3745	3756	3715
	female	4239	4290	3850	4165	4144	4026	4183	3951	4106		

Table 3- 2. The formants of Strad and non-Strad violins comparisons with vocals.

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3.2.3. Formant differences

All the formants shift when the musical note changes, so we analyze whether the formants of the Stradivari have a significant difference with the non-Stradivari in each musical note. All the results are showed in Figure 3- 7. In F1, there are significant difference in the musical note of B3, C4#, D4, D4#, E4 and F4. The notes from C4# to F4 of the Stradivari are all higher than the non-Stradivari. Interestingly, it proves that the trend with the rising pitch is different between the Stradivari and the non-Stradivari. In F3, there are significant difference in the note of A3# and G4. In both F2 and F4, none of the note has a significant difference between the two violins. To sum up, we find that the trend of F1 can be a kind of characteristic for the Stradivari.

Without considering the influence on the musical note, there are 72 samples (6 violins × 12 musical notes) in the group of the Stradivari and 108 samples (9 violins × 12 musical notes) in the group of the non-Stradivari. In Figure 3- 8, the p-values of F1, F2 and F3 are all below 0.01, and the result shows that the three formants of the Stradivari have a significant difference with the non-Stradivari. We do not find the significant difference between these two groups in the fourth formant. Besides, all the medians of the four Stradivari violin formants are higher than the non-Stradivari.

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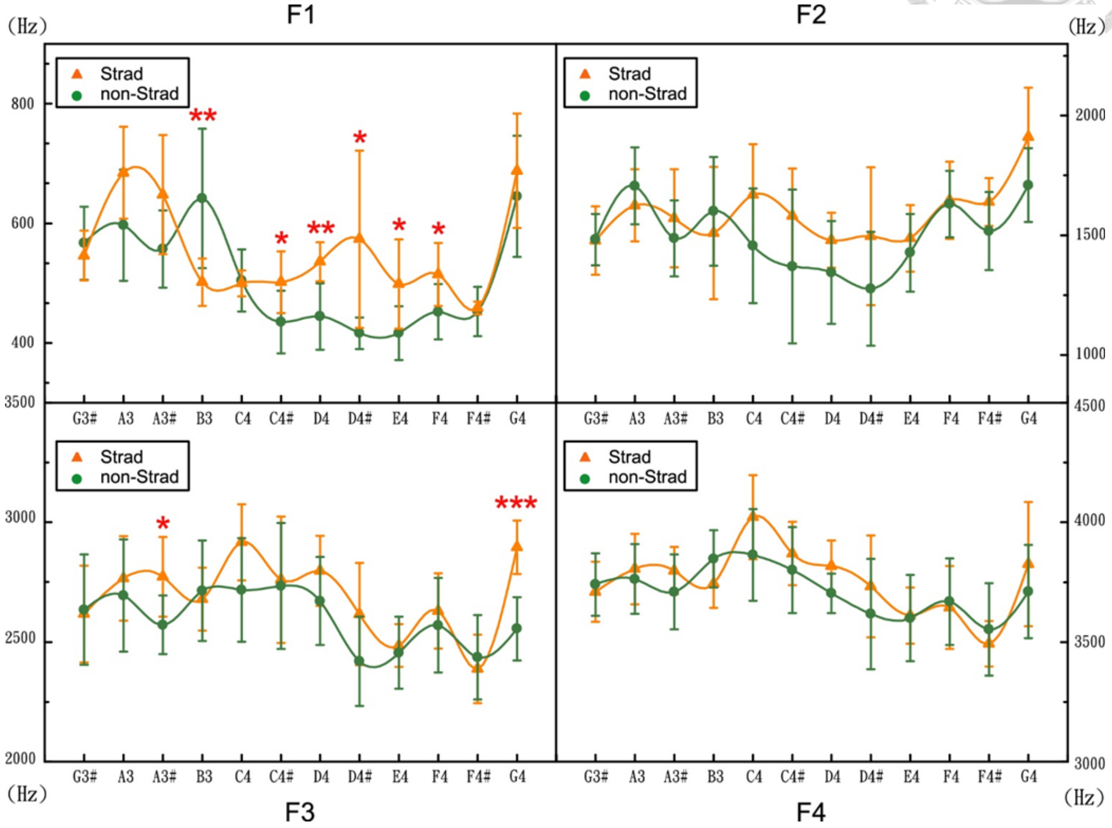

Figure 3- 7. Formant comparisons in each musical note between Strad and non-Strad violins. The two-tailed Welch's t-test is used. The symbol * indicates $0.01 < p < 0.05$, ** indicates $0.001 < p < 0.01$ and *** indicates $p < 0.001$. n = 6 for the Strads and n = 9 for the non-Strads.

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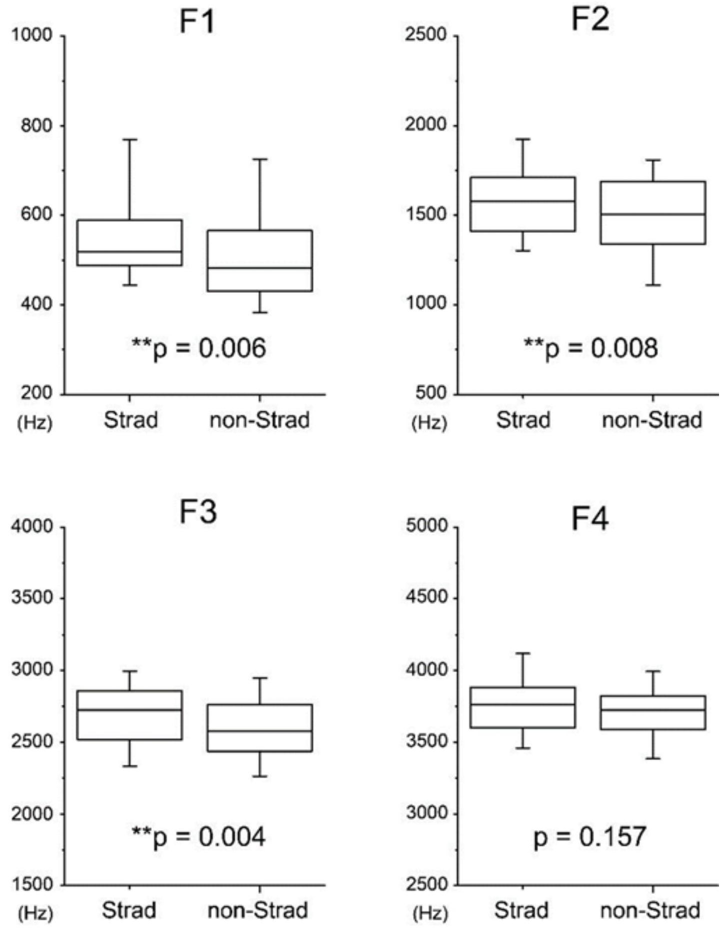

Figure 3- 8. Formant comparisons in an octave between Strad and non-Strad violins. The two-tailed Welch's t-test is used. The symbol * indicates $0.01 < p < 0.05$, ** indicates $0.001 < p < 0.01$ and *** indicates $p < 0.001$. n = 72 for the Strads (6 violins × 12 musical notes) and n = 108 for the non-Strads (6 violins × 12 musical notes). The box represents the first and third quartiles, the middle band represents the median, and the whiskers represent the 5^{th} and 95^{th} percentiles.

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3.2.4. Vowel qualities

In Figure 3- 9 a, we plot every note one by one (6 Strads and 9 non-Strads over 12 pitches each), and we find almost every note is in the region of the vowel chart again (Appendix- 7). In the vowel height, 56 % of the Stradivari notes are under 9, and there are only 46 % for the non-Stradivari notes. In the vowel backness, 75% of the Stradivari notes are in front of the middle line and there are only 62 % for the non-Stradivari notes. Both the results in the vowel height and backness explain why the average of the Stradivari in the vowel chart is lower and more forward than the non-Stradivari in Figure 3- 9 b. The mean value of the non-Stradivari is similar to the Amati and the da Salo in Figure 3- 4. On the other hand, the mean value of the Stradivari is closer to [ɛ] and [ɝ]. In the research of acoustic phonetics, humans perceive that the front vowels are brighter than the back vowels,[52-55] and the symbolism of open vowels are bigger than the close vowels.[56-58] The brilliant and sparkling sound of the Stradivari violins may be partly attributed to these reasons.

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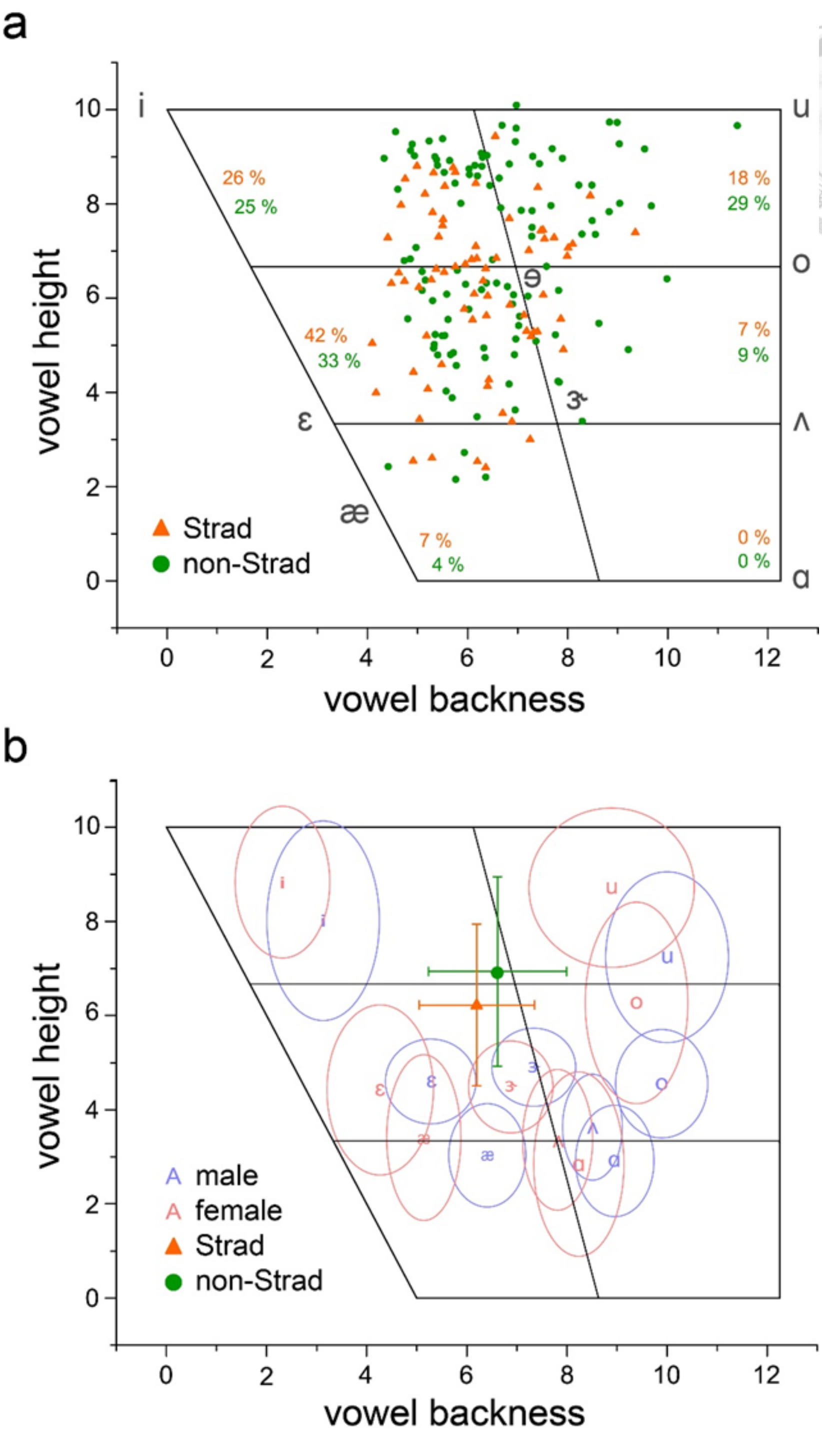

Figure 3- 9. Vowel quality comparisons between Strad and non-Strad violins. (a) Vowel backness and height of individual violin notes (6 Strads and 9 non-Strads over 12 pitches each). (b) The mean backness and height of each violin group are represented by the position of the IPA vowel symbol. The centers of each ellipse are the mean backness and height of the 8 males and the 8 females we recorded. The lengths and widths of each ellipse represent the standard deviations. The average values of each violin group are represented by colored shapes, and the vertical and horizontal whiskers represent the standard deviations.

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3.2.5. Gender qualities

In Figure 3- 10 a, every note (6 Strads and 9 non-Strads over 12 pitches each) is also in the region of the vocals (Appendix- 8). In F3, 54% of the Stradivari notes are above 2700 Hz, and there are only 32 % for the non-Stradivari notes. In F4, 45% of the Stradivari notes are above 3800 Hz, which is the lower limit of females, and there are only 33 % for the non-Stradivari notes. Both the results in F3 and F4 explain why the F3 average of the Stradivari is higher than the non-Stradivari, but the F4 average of the Stradivari is almost the same as the non-Stradivari in Figure 3- 10 b.

To know the gender qualities more instinctively, we approximate the vocal tract length of each group in Figure 3- 11. The mean VTL of the Stradivari violins is 16.2 cm, as opposed to 17.0 cm for the non-Stradivari violins. Comparing with the anatomical VTL of singers,[33] the Stradivari violins have the characteristics of tenors or altos, and the non-Stradivari violins are similar to basses or baritones.

Need to be reminded, when Amati and 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, before the birth of Stradivari.[59] Around the end of Stradivari's career, the popularity of sopranos had risen, being considered as the most attractive voice type.[60] This evolutionary trend is also consistent with the evolution of violins we find.

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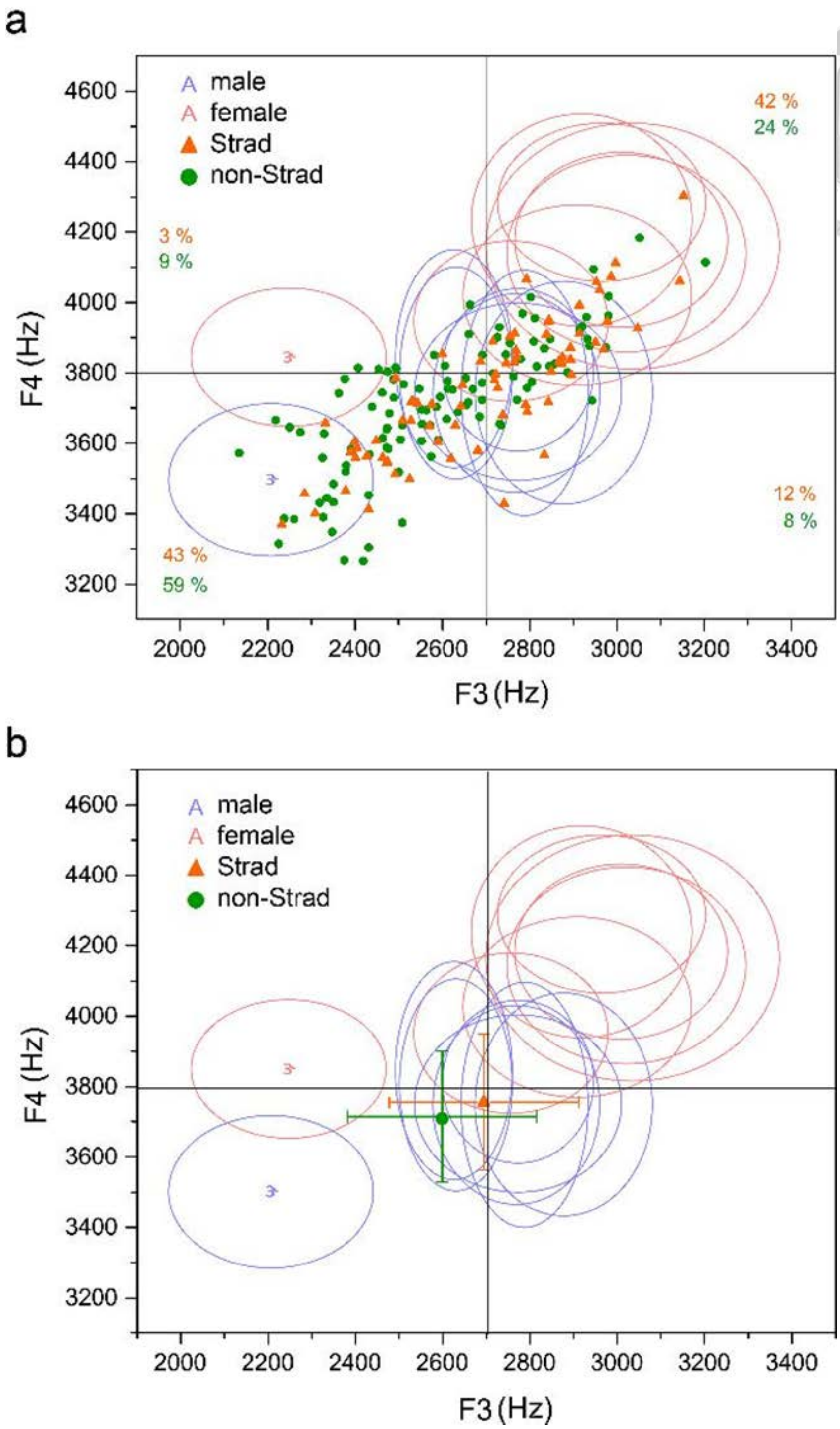

Figure 3- 10. F3 and F4 distribution comparisons between Strad and non-Strad violins. (a) F3 and F4 values of individual violin notes (6 Strads and 9 non-Strads over 12 pitches each). (b) The centers of each ellipse are the mean values of the 8 males and the 8 females we recorded. The lengths and widths of each ellipse represent the standard deviations. The average values of each violin group are represented by colored shapes, and the vertical and horizontal whiskers represent the standard deviations.

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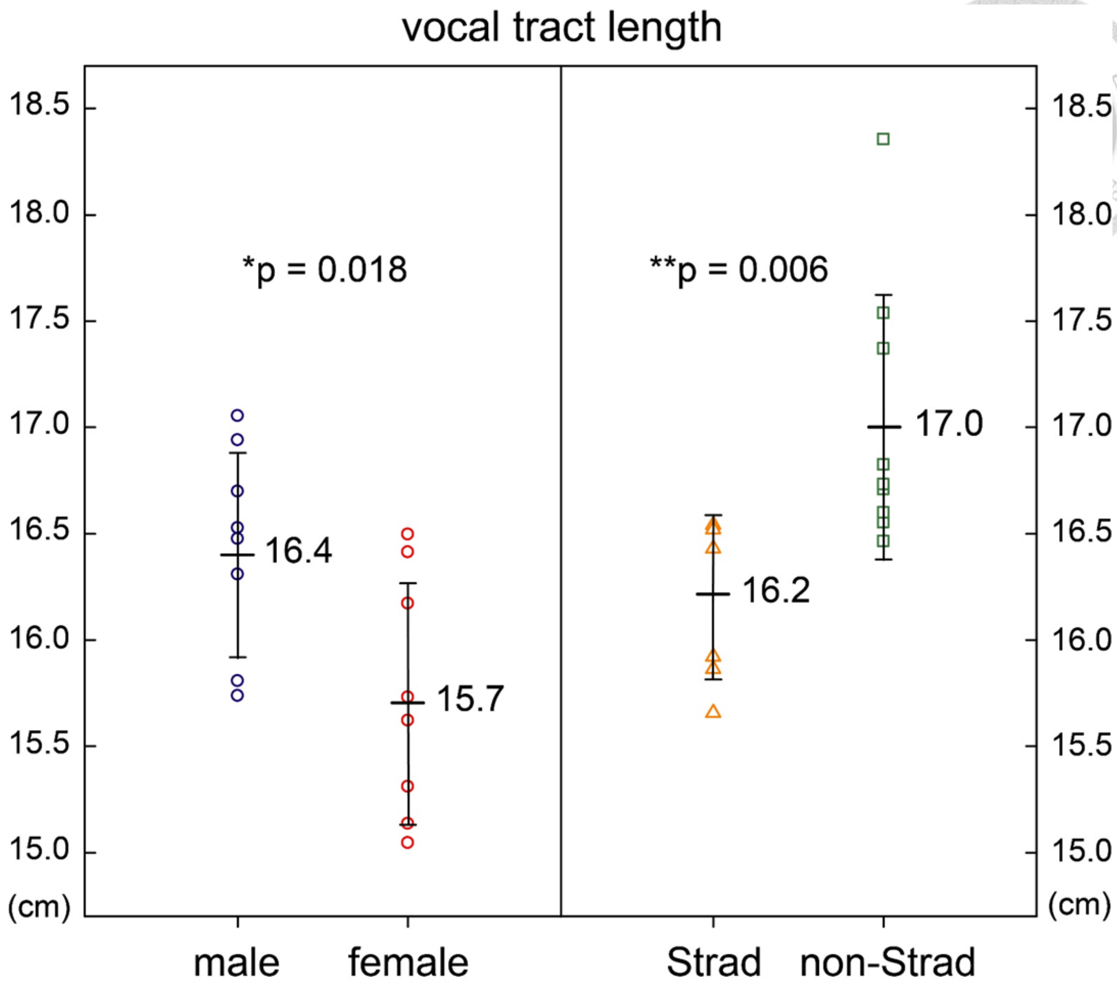

Figure 3- 11. Vocal tract length estimates for males vs. females, and Strad vs. non-Strad violins. Open colored shapes represent the individual data points, the center band represents the means, and the whiskers represent the standard deviations. The two-tailed Welch's t-test is used. The symbol * indicates $0.01 < p < 0.05$ and the symbol ** indicates $0.001 < p < 0.01$. For male , female, Strad and non-Strad groups, n = 8, 8, 6 and 9, respectively.

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Chapter 4 Discussions

Based on our results, the sound of violin can be analogous to vocals, as both have similar formants. From this perspective, we find that Stradivari violins exhibit higher formants than the other old Italian violins, and the formants from F1 to F3 all have a significant difference between them. We suspect that some chemical manipulations may have altered the stiffness of wood. In turn, stiffness changes may affect the natural vibration frequencies of the plate and the formants of violin. Here, we discuss a plausible link between wood treatments in Stradivari violins and unique acoustic properties.

Construction design can be imitated.

The violin components and their structure can be imaged by computed x-ray tomography (Figure 4- 1).[61-62] The size, the arching, the thickness and the shape of f-holes all can be further analyzed in detail. To have more power and a good response for the public concert increased at that time, Stradivari violins have lower arching and longer f-holes than the violins before.[1, 25-26] However, even though luthiers tried to imitate all the construction designs of Stradivari violins, they could not reproduce the sound. Based on this observation, we suggest that the secrets of Stradivari may lie in the material property.

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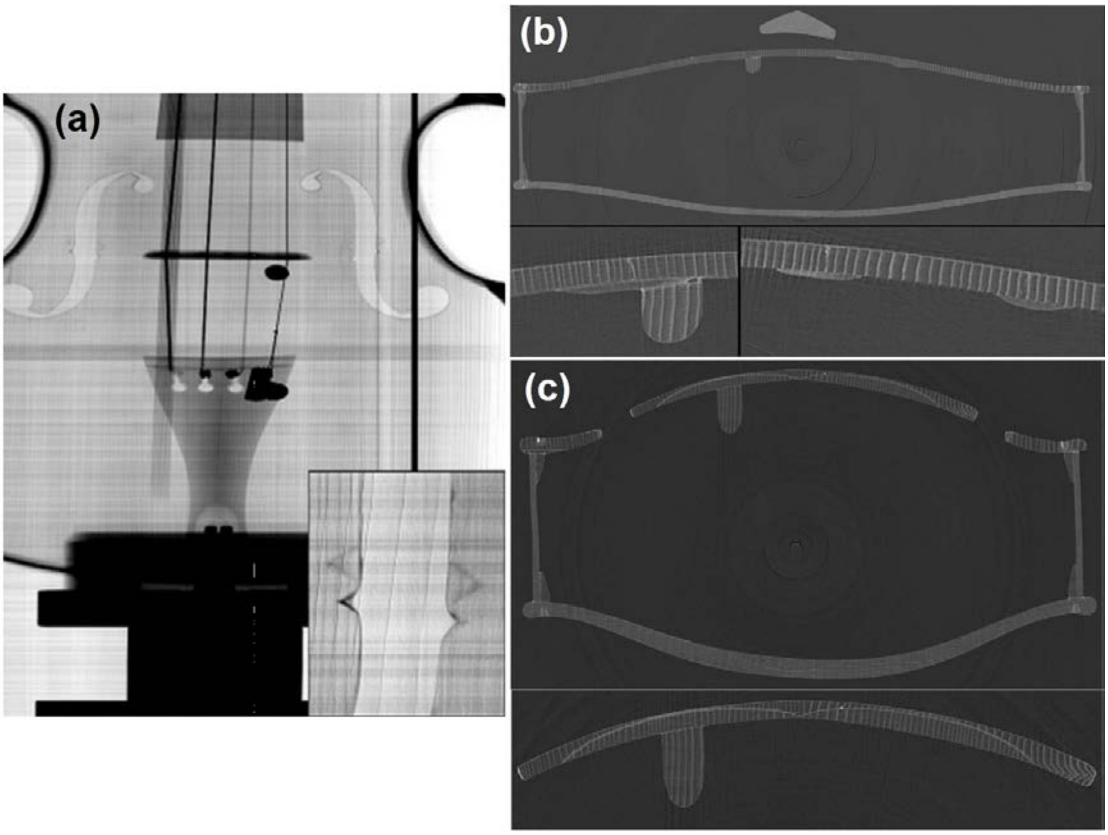

Figure 4- 1. X-ray image of a Guadagnini violin.

(a) 2D image. The inset shows the modification of the f-hole. (b) Tomographic slice at the tailpiece level. The left inset shows the bass bar glued on a patch, while the right inset shows two additional patches on the top plate. (c) Tomographic slice at the strings bridge. The inset shows two wooden patches applied on the top plate.[61]

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The secrets are in the resonant chamber.

The modernization of Baroque violins involve replacing many components, including the neck, fingerboard, bassbar, soundpost, strings and bridge.[63-64] After the replacement, the violins can be played loudly and respond faster. We believe that the secrets that affect the unique sound are in the resonant chamber which has not be replaced. Therefore, we focus on the material property of the chamber later.

The elevated formants are affected by the top plate.

According to Bissinger's work, the resonance frequency around 3500 Hz, which is close to F4, is affected by the rocking mode of bridge.[23] But it shows no significant difference between the Strad and the others in our data.

Vibrations between 1200 and 2500 Hz, which govern F2 and F3, are affected by the island area (between the f-holes) related to the top plate (Figure 4- 2).[24, 65] Vibrations around 500 Hz, which are close to F1, are affected by the $B1^-$ and $B1^+$ modes of the top plate. In our data, all the three formants are elevated, so we suggest that the elevated formants are caused by the elevated natural frequencies of the top plate.

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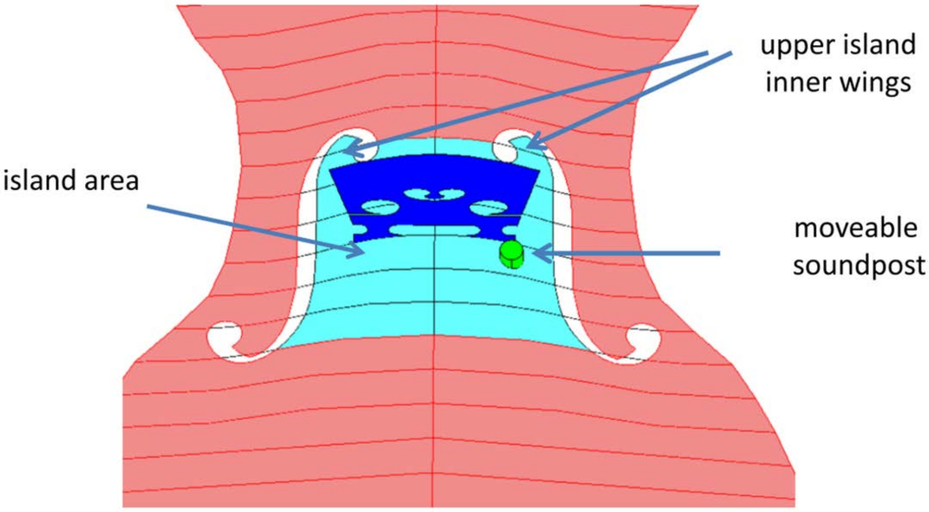

Figure 4- 2. The scheme of the island area.
This figure is adopted from Gough et al., 2018.[65]

Based on Hook's law and the equations of motion (equation (**4**)), with the mass tensor [M] and the stiffness tensor [K], the displacement vector <u> and the acceleration vector <ü> can be solved. The displacement vector can be assumed to be a linear combination of a series of natural modes $<\varphi>_i$, and each of natural vibration frequency ω_i can be solved. Based on the equation (**5**), we can know that elevated natural frequencies are caused by higher stiffness.

$$[\mathbf{M}]\langle \ddot{\mathrm{u}} \rangle + [\mathbf{K}]\langle \mathrm{u} \rangle = 0 \qquad (\mathbf{4})$$

$$([\mathbf{K}] - \omega_i{}^2[\mathbf{M}])\langle \varphi \rangle_i = \langle 0 \rangle \qquad (\mathbf{5})$$

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Before discussing the stiffness of the top plate, we should know wood is an anisotropic material, which has different mechanical properties in different directions (Figure 4- 3).[66] In most cases, to calculate the stiffness tensor of wood, the cylindrical coordinate is used.[67]

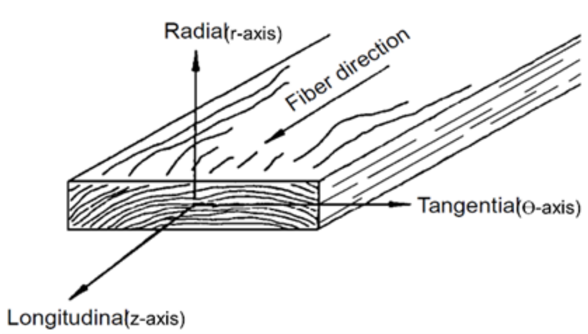

Figure 4- 3. Three principal axes of wood.
This figure is adopted from Green et al., 1999.[66]

The stiffness tensor can be constructed by elastic modulus (*E*), shear modulus (*G*) and Poisson's ratio (*v*) in each direction (equation (**6**)). These constants are used to define the relationship between the stress and the strain. With measurement of these constants, natural frequencies can be calculated.[68-70]

$$[\mathbf{K}] = [\boldsymbol{C}]^{-1} = \begin{bmatrix} \frac{1}{E_r} & -\frac{v_{r\Theta}}{E_r} & -\frac{v_{rz}}{E_r} & 0 & 0 & 0 \\ -\frac{v_{\Theta r}}{E_\Theta} & \frac{1}{E_\Theta} & -\frac{v_{\Theta z}}{E_\Theta} & 0 & 0 & 0 \\ -\frac{v_{zr}}{E_z} & -\frac{v_{z\Theta}}{E_z} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{r\Theta}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{\Theta z}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{rz}} \end{bmatrix}^{-1} \qquad (\mathbf{6})$$

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Chemistry of the top plate should be considered.

The higher formants may come with the higher elastic modulus of the top plate. In violins, we should focus on the modulus in the two directions, the z-axis from the tailpiece to the fingerboard and the r-axis from one f-hole to the other f-hole. Although the previous studies have provided little data about the modulus of violins due to the difficulty of measuring,[71] we try to discuss it from the cumulative knowledge of wood literature.

The elastic modulus of wood depends on cell wall properties which can be affected by aging or modified by thermal treatments and chemical manipulations.[72-73] To understand how to control cell wall properties more deeply, we need to discuss the composition and the structure of cell wall.

One of the main components of cell wall is cellulose, which is around 40-50 weight percentage in dry wood.[74-75] Cellulose (Figure 4- 4 a)[76] is a polysaccharide consisting of a linear chain of 7000-15000 $\beta(1\rightarrow4)$ linked D-glucose units.[77-78] The cellulose molecules are aligned to form microfibrils of which the diameter is about 3-4 nm.[79] The cellulose microfibrils then aggregate into macrofibrils, of which the diameter is about 10-25 nm (Figure 4- 4 b).[80] The matrix of hemicellulose (25-35%) and lignin (20-30%) also play important roles in the aggregation and the mechanical properties of wood (Figure 4- 5).[81-84] Hemicellulose is the most hygroscopic substance in wood.[85] Wood

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cell walls are composed of different layers which have different cellulose fibril angles (Figure 4- 4 c). As a cell grows, the primary cell wall layer is first secreted. The enzymes make the cellulose fibrils in this layer distributed randomly, reducing the yield strength of the walls and allowing the significant deformation.[86-87] Afterward, with the maturation of the cell, the three secondary layers, S1, S2 and S3, are formed consecutively. The S1 layer affects the modulus of the r-axis, as a result of the circumferential orientation of the fibrils and the properties of the matrix constituents,[88] especially hemicellulose. The S2 layer affects the modulus of both the r-axis and z-axis, as a result of the alignment orientation of fibrils and the high volume fraction.[81, 89] The S3 layer is believed to resist the hydrostatic pressure within the cell.[90] Due to the complexity of the cell wall, the whole picture remains unresolved. Nevertheless, that the elastic modulus of wood depends on the composition and the structure of cell wall.

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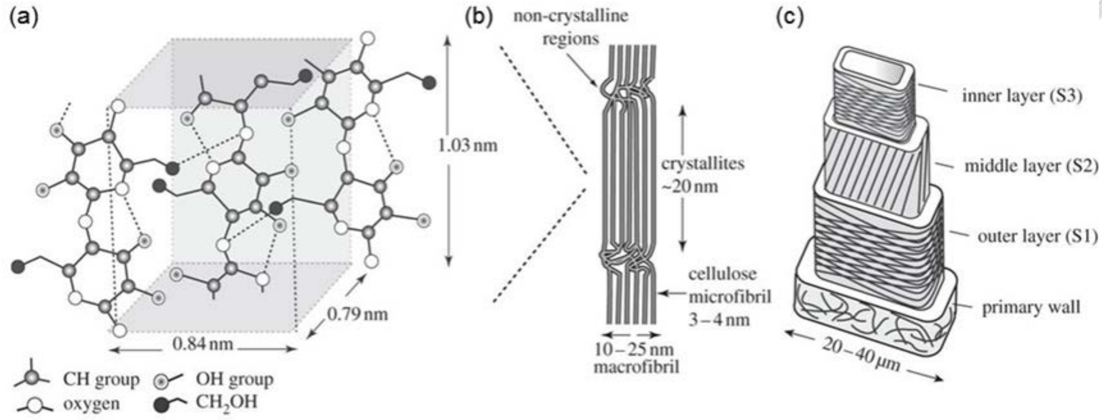

Figure 4- 4. The structure of cellulose.

(a) The molecular structure of cellulose, with glucose molecules alternately rotated 180°. The solid lines are used to indicate the covalent bonds, and the dashed lines are used to indicate the hydrogen bonds. (b) The cellulose microfibrils, with both crystalline and non-crystalline regions, aggregate into a macrofibril. (c) The cell wall of wood, made up of a primary layer and three secondary layers (S1, S2 and S3), with fibrils arranged in different orientations in each layer.[77]

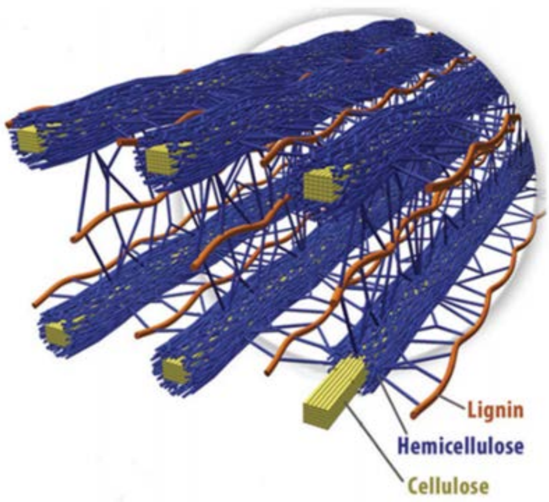

Figure 4- 5. Spatial arrangement of the matrix and the cellulose microfibrils.

The matrix is mainly composed of the hemicellulose and the lignin.[82]

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Factors that enhance the elasticity of the top plate.

Compared to the other components in wood, hemicellulose is the most reactive because of its amorphous structure and weaker glycosidic linkages. The half-life of hemicellulose decomposition was estimated around 300-500 years, so the effect of aging should be considered in historical violins.[2, 91] When the percentage of hemicellulose decreases, due to reduced hygroscopicity and the lower elastic modulus of hemicellulose compared to cellulose, the elastic modulus of the wood increases.[77, 88, 92-93] However, we have no evidence that whether the aging process of Stradivari violins is different from the other historical violins.

Heat treatment is a common modification method of wood in the recent centuries. In the range of low temperature (70-180°C), it can mimic accelerated aging, with the decrease of hemicellulose and the increase of elastic modulus.[94] But it may also cause the oxidation or rearrangement of lignin, changing the mechanism of aging. In the range of higher temperatures (180-250°C), the amorphous carbohydrate components degrade and the relative amount of the crystalline cellulose increases,[95-96] and the change of elastic modulus depends on the wood species.[72, 97-98] However, from 16th to 18th century in Italy, there is no record showing that luthiers manufactured violins with heating in high temperature, and there is no evidence that the historic violins have ever been heated.

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Wood preservation by mineral manipulation had a long history in Italy and surrounding countries due to the demand of mechanical properties, moisture resistance, biological durability and fire resistance.[2, 73, 99-100] The reactions may be formed by filling the cell lumens with mineral solution, and the metal ions may cross-link between multiple OH groups of the cell wall polymers. The mineral effect on the acoustics of wood of musical instruments was first noted in 1580.[101] But how the different chemicals influence the elastic modulus are still unknown.

In the recent publication of our group about Stradivari's maple, we found that cellulose had no apparent changes, but one-third of the hemicellulose had decomposed. Lignin oxidation was observed and complex minerals were added.[2] The result that minerals were added is agreement with the previous literatures,[100, 102] and it is very likely that spruce plates in Cremonese violins have also been chemically manipulated.

In summary, previous research proved that the elastic modulus in the z-axis is mainly affected by the cellulose in the S2 layers.[88] Because aging has little effect on the cellulose,[2, 103] if the modulus in the z-axis is enhanced, it may be attributed to the mineral treatment that causes the metal chelating.

The elastic modulus in the r-axis is affected by the composition percentage of cellulose, hemicellulose and lignin, and their interaction.[88] Due to the lower elastic modulus of hemicellulose and lignin, when their levels decrease, the elastic modulus of

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wood increases.[77, 88, 93] Besides, aging or mineral treatment may also cause the elevated elastic modulus in the r-axis. In our recent experiment, alkali treatment also has a large effect on the wood composition, but more evidence should be acquired.

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Chapter 5 Conclusions

In our experiments, the linear predictive coding method was confirmed to be an impressive method to find the formants of violins. With these formants, the violins were compared to the singing voice. Moreover, the violin formants shifted with the different musical notes.

The two early examples of Italian violins (1570 Andrea Amati and 1560 Gasparo da Salo) both showed the four voice-like formants (F1-F4) below 5000 Hz. The F1 and F2 values mapped to the central region on the international phonetic alphabet (IPA) vowel diagram, and the calculated vocal tract lengths (VTL) were correspondent to the basses/baritones. The results implied that the first acoustic landmark devised by the violin inventors appeared to mimic the male singing voices.

The Stradivari violins had different acoustic characteristics from the other old Italian violins. In the frequency response, the Stradivari showed two strong formants at 2766 and 3144 Hz, and showed two strong anti-formants at 1219 and 2344 Hz. In the formant analysis, through the t-test, the Stradivari had significant differences from the other old in F1 through F3. Besides, elevated F1 and F2 for the Stradivari led to decreased vowel height and backness in the IPA vowel diagram, shifting toward brighter and bigger sounding vowels. Shorter VTL gave the Stradivari's notes greater resemblance to tenors/altos. The results implied that the second acoustic landmark

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devised by Stradivari appeared to mimic the female singing voices. The unique vowel and gender qualities associated with the Stradivari violins correlated well with centuries-old observations about their unusual brilliance.

The tonal improvement going from Amati to Stradivari violins has been historically attributed to the lower plate arching in the latter, but recent evidence also suggested that chemical treatment of wood has altered its material properties. The combined properties of arching and wood properties of the top plate may be the reason for the higher formants in F1 through F3 for the Stradivari violins. We hope that our finding and discussions in formant analysis could help the violin researchers connect the material chemistry and the construction design to acoustic characteristics in the future.

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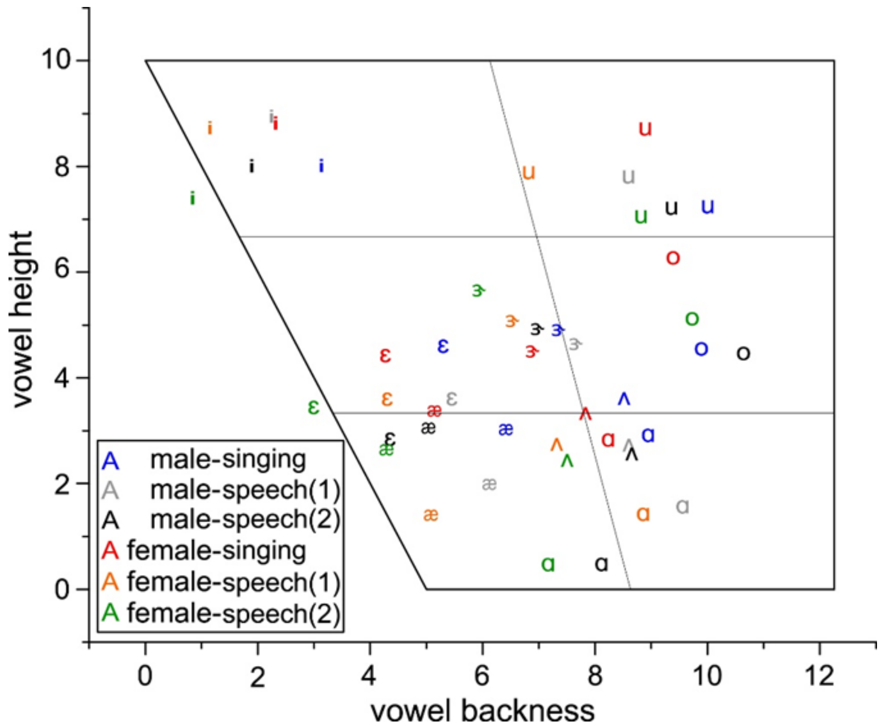
Appendix

male	had	head	heard	heed	hod	hoed	hud	who'd
b-Avg	6.41	5.29	7.34	3.13	8.94	9.89	8.51	10.00
b-SD	0.77	0.90	0.84	1.13	0.80	0.92	0.60	1.22
h-Avg	3.03	4.60	4.90	8.01	2.92	4.55	3.62	7.24
h-SD	1.09	0.90	0.83	2.12	1.19	1.15	1.13	1.81
female	**had**	**head**	**heard**	**heed**	**hod**	**hoed**	**hud**	**who'd**
b-Avg	5.14	4.27	6.88	2.32	8.24	9.39	7.83	8.89
b-SD	0.74	1.06	0.84	0.94	0.90	1.02	0.71	1.65
h-Avg	3.39	4.42	4.49	8.83	2.83	6.28	3.36	8.69
h-SD	1.74	1.81	0.97	1.61	1.94	2.14	1.49	1.65

unit: Hz

Appendix- 1. The coordinate values of sung vowels on the IPA vowel chart.

The symbol b is the vowel backness, and the symbol h is the vowel height.



Appendix- 2. Comparison of spoken and sung vowels we recorded.

1: The data from Childers (Table 1-1). 2: The data from Hillenbrand. (Table 1-2).

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Amati 1570	G#3	A3	A#3	B3	C4	C#4	D4	D#4	E4	F4	F#4	G4	Avg.
b	6.01	5.08	5.79	5.56	7.81	7.28	5.86	4.93	6.27	6.44	6.02	5.77	6.07
h	5.79	6.19	6.62	4.06	6.19	7.53	8.04	9.05	9.10	8.42	8.77	4.60	7.03
da Salo 1560	G#3	A3	A#3	B3	C4	C#4	D4	D#4	E4	F4	F#4	G4	Avg.
b	5.49	5.54	6.89	6.36	7.03	4.85	6.68	8.82	6.96	6.29	5.22	6.65	6.40
h	5.23	5.23	5.90	2.22	5.64	6.86	9.69	9.77	9.64	9.02	9.37	7.95	7.21

unit: Hz

Appendix- 3. The coordinate values of the Amati and the da Salo on the IPA vowel chart.

male	had	head	heard	heed	hod	hoed	hud	who'd
F3-Avg	2647	2626	2207	2772	2787	2877	2773	2769
F3-SD	145	134	234	237	145	203	172	192
F4-Avg	3805	3845	3501	3752	3748	3749	3813	3748
F4-SD	301	310	216	252	349	317	231	282
female	had	head	heard	heed	hod	hoed	hud	who'd
F3-Avg	2918	2964	2247	3034	3021	2908	3008	2756
F3-SD	253	238.2	223	336	274	262	244	222
F4-Avg	4239	4290	3850	4165	4144	4026	4183	3951
F4-SD	301	224	196	349	280	256	249	228

unit: Hz

Appendix- 4. The F3 and F4 values of sung vowels.

Amati 1570	G#3	A3	A#3	B3	C4	C#4	D4	D#4	E4	F4	F#4	G4	Avg.
F3	2785	2331	2433	2728	2692	2757	2847	2803	2327	2395	2349	2781	2602
F4	3970	3628	3453	3901	3773	3885	3820	4016	3559	3577	3349	3840	3731
da Salo 1560	G#3	A3	A#3	B3	C4	C#4	D4	D#4	E4	F4	F#4	G4	Avg.
F3	2612	2661	2434	2655	2574	2922	2510	2329	2352	2320	2392	2421	2515
F4	3669	3716	3569	3785	3652	3933	3652	3391	3485	3432	3584	3265	3594

unit: Hz

Appendix- 5. The F3 and F4 values of the Amati and the da Salo.

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Strad	F1	F2	F3	F4
Dubois 1667	537	1539	2670	3745
Dushkin 1707	558	1654	2690	3799
Viotti 1709	531	1519	2702	3797
Wirth 1713	538	1631	2812	3814
Elman 1722	560	1496	2628	3645
Omobono 1740	601	1705	2660	3736
Avg.	554	1591	2694	3756
non-Strad	**F1**	**F2**	**F3**	**F4**
Andrea Amati 1570	503	1583	2602	3731
Gasparo da Salo 1560	497	1509	2515	3594
Paolo Maggini 1610	517	1571	2649	3817
Nicolo Amati 1624	543	1517	2617	3635
Nicolo Amati 1656	505	1360	2582	3707
Francesco Ruggeri 1694	482	1314	2436	3681
Filius Andrea 1706	492	1582	2733	3774
Carlos Bergonzi 1732	532	1484	2688	3750
del Gesu Lafont 1733	525	1585	2559	3744
Avg.	511	1500	2598	3715

Appendix- 6. The mean F1 to F4 values of the recoded antique violins.

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Strad		**G#3**	**A3**	**A#3**	**B3**	**C4**	**C#4**	**D4**	**D#4**	**E4**	**F4**	**F#4**	**G4**	**Avg.**
Dubois 1667	b	7.32	6.89	6.85	9.35	6.37	7.41	6.31	8.45	6.13	4.67	5.00	4.18	6.58
	h	5.26	3.36	5.84	7.37	6.61	8.33	6.35	8.15	6.07	7.95	8.78	3.97	6.50
Dushkin 1707	b	6.43	5.05	5.30	6.09	5.38	6.11	6.41	7.73	6.17	5.15	5.55	4.41	5.81
	h	4.25	3.40	2.59	6.80	6.60	5.52	6.03	7.27	7.08	8.20	8.36	7.27	6.11
Viotti 1709	b	6.38	6.40	7.92	5.28	7.47	6.19	7.23	7.54	6.56	5.31	5.76	5.21	6.44
	h	5.61	4.11	4.89	6.37	7.41	6.82	6.99	7.24	9.42	7.80	8.65	4.05	6.61
Wirth 1713	b	7.52	6.20	5.19	5.54	4.75	8.10	5.96	5.52	6.84	5.51	5.72	4.10	5.91
	h	6.05	2.51	5.18	6.53	6.34	7.13	6.70	7.65	7.67	7.53	8.75	5.02	6.42
Elman 1722	b	7.40	7.28	7.25	7.87	4.48	4.63	7.99	7.19	8.02	7.51	6.17	6.57	6.86
	h	5.27	5.16	2.98	5.54	6.29	6.52	6.87	5.28	7.05	7.43	8.42	6.83	6.14
Omobono 1740	b	5.49	6.37	6.70	5.04	5.76	5.43	7.13	4.92	5.33	5.94	4.76	4.93	5.65
	h	4.57	2.38	3.53	6.21	6.65	7.29	5.62	2.52	8.64	5.75	8.51	4.42	5.51
non-Strad		**G#3**	**A3**	**A#3**	**B3**	**C4**	**C#4**	**D4**	**D#4**	**E4**	**F4**	**F#4**	**G4**	**Avg.**
Andrea Amati 1570	b	6.01	5.08	5.79	5.56	7.81	7.28	5.86	4.93	6.27	6.44	6.02	5.77	6.07
	h	5.79	6.19	6.62	4.06	6.19	7.53	8.04	9.05	9.10	8.42	8.77	4.60	7.03
Gasparo da Salo 1560	b	5.49	5.54	6.89	6.36	7.03	4.85	6.68	8.82	6.96	6.29	5.22	6.65	6.40
	h	5.23	5.23	5.90	2.22	5.64	6.86	9.69	9.77	9.64	9.02	9.37	7.95	7.21
Paolo Maggini 1610	b	6.34	6.27	7.20	6.18	5.95	5.09	5.39	7.89	7.27	5.52	6.19	4.79	6.17
	h	4.77	6.20	6.07	3.51	6.32	6.59	8.85	9.00	7.34	8.70	8.63	5.59	6.80
Nicolo Amati 1624	b	6.94	5.93	6.32	5.75	5.34	9.66	6.37	8.82	7.68	5.63	5.74	4.96	6.60
	h	3.65	2.75	4.97	2.18	9.03	7.99	6.35	7.86	9.20	8.95	8.47	7.10	6.54
Nicolo Amati 1656	b	7.80	5.31	7.74	9.20	8.48	9.02	9.03	8.48	6.95	4.86	8.21	5.60	7.56
	h	4.26	4.96	5.25	4.93	7.68	9.30	8.04	8.42	9.35	9.16	8.42	5.57	7.11
Francesco Ruggeri 1694	b	8.28	6.93	7.82	7.01	9.97	11.38	8.98	9.53	6.96	5.37	6.38	4.60	7.77
	h	3.42	4.82	4.24	5.44	6.44	9.69	9.75	9.20	10.12	8.97	9.05	8.34	7.46
Filius Andrea 1706	b	7.36	5.34	7.57	4.73	5.29	6.03	7.28	6.14	5.49	4.32	4.89	6.82	5.94
	h	5.12	5.25	6.70	6.82	5.98	8.65	7.88	8.85	9.41	9.00	9.30	4.20	7.26
Carlos Bergonzi 1732	b	6.96	5.71	5.65	8.62	6.57	7.66	8.28	7.43	7.06	5.15	6.49	6.91	6.87
	h	5.16	4.87	4.83	5.50	6.35	7.99	7.39	8.88	7.89	6.41	6.84	6.10	6.52
del Gesu Lafont 1733	b	6.79	4.40	5.68	5.33	5.58	6.83	8.54	6.63	4.56	6.28	7.29	5.40	6.11
	h	6.27	2.45	3.91	5.04	6.11	8.87	7.38	8.58	9.56	8.83	9.04	4.82	6.74

Appendix- 7. The coordinate values of the recoded antique violins on the IPA vowel chart.

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Strad		G#3	A3	A#3	B3	C4	C#4	D4	D#4	E4	F4	F#4	G4	Avg.
Dubois 1667	F3	2533	2728	2647	2571	2716	2688	2868	2473	2631	2644	2621	2915	2670
	F4	3723	3761	3769	3654	3893	3836	3837	3547	3655	3708	3561	3997	3745
Dushkin 1707	F3	2530	2962	2979	2544	2766	2767	2846	2390	2494	2682	2475	2845	2690
	F4	3722	4039	3951	3719	3835	3916	3955	3577	3789	3584	3553	3949	3799
Viotti 1709	F3	2850	2769	2723	2771	2915	2755	2844	2406	2402	2601	2400	2987	2702
	F4	3809	3868	3801	3850	3915	3907	3722	3591	3562	3858	3608	4077	3797
Wirth 1713	F3	2464	2894	2971	2876	3153	2875	2952	2840	2492	2896	2285	3048	2812
	F4	3562	3842	3871	3848	4307	3831	3891	3913	3517	3798	3460	3930	3814
Elman 1722	F3	2429	2450	2740	2591	2998	3144	2529	2795	2380	2432	2310	2743	2628
	F4	3568	3611	3684	3608	4117	4064	3668	3693	3468	3417	3404	3432	3645
Omobono 1740	F3	2895	2791	2577	2720	2954	2333	2748	2794	2511	2526	2233	2835	2660
	F4	3875	3713	3714	3785	4062	3661	3831	4070	3670	3502	3373	3571	3736
non-Strad		**G#3**	**A3**	**A#3**	**B3**	**C4**	**C#4**	**D4**	**D#4**	**E4**	**F4**	**F#4**	**G4**	**Avg.**
Andrea Amati 1570	F3	2785	2331	2433	2728	2692	2757	2847	2803	2327	2395	2349	2781	2602
	F4	3970	3628	3453	3901	3773	3885	3820	4017	3559	3577	3349	3840	3731
Gasparo da Salo 1560	F3	2612	2661	2434	2655	2574	2922	2510	2329	2352	2321	2393	2421	2515
	F4	3669	3717	3569	3785	3652	3933	3651	3391	3485	3431	3584	3265	3594
Paolo Maggini 1610	F3	2818	2490	2555	2664	2732	3204	2858	2251	2464	2513	2625	2608	2649
	F4	3819	3730	3655	3995	3930	4115	3826	3646	3745	3768	3753	3821	3817
Nicolo Amati 1624	F3	2477	2795	2554	2981	2596	2764	2945	2227	2440	2510	2433	2686	2617
	F4	3585	3758	3696	3964	3732	3790	3722	3316	3704	3375	3305	3676	3635
Nicolo Amati 1656	F3	2637	2915	2497	2588	2456	2671	2733	2262	2381	2835	2352	2662	2582
	F4	3690	3924	3813	3704	3811	3755	3656	3385	3537	3870	3433	3910	3707
Francesco Ruggeri 1694	F3	2615	2506	2693	2276	2474	2337	2480	2364	2380	2476	2219	2409	2436
	F4	3755	3611	3852	3632	3639	3445	3686	3743	3520	3805	3666	3814	3681
Filius Andrea 1706	F3	2692	2977	2554	2933	3053	2773	2576	2549	2565	2888	2737	2494	2733
	F4	3724	3872	3607	3897	4184	3724	3562	3755	3695	3803	3653	3816	3774
Carlos Bergonzi 1732	F3	2938	2592	2814	2849	2947	2806	2655	2502	2377	2717	2582	2475	2688
	F4	3877	3610	3957	3897	4095	3774	3709	3518	3268	3799	3851	3644	3750
del Gesu Lafont 1733	F3	2136	2983	2614	2747	2932	2378	2440	2489	2811	2473	2239	2465	2559
	F4	3573	4018	3777	3853	3959	3784	3704	3781	3890	3589	3387	3615	3744

Appendix- 8. The F3 and F4 values of the recoded antique violins

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