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A Comparison of Viola Strings with Harmonic Frequency Analysis

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A COMPARISON OF VIOLA STRINGS

WITH HARMONIC FREQUENCY ANALYSIS

by

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Many brands of viola strings are available today. Different materials used result in varying timbres. This study compares 12 popular brands of strings. Each set of strings was tested and recorded on four violas. We allowed two weeks after installation for each string set to settle, and we were careful to control as many factors as possible in the recording process. The recordings include individual note samples of 8 seconds each and performances of the prelude from the first Bach cello suite. For this study, we recorded 576 note samples and 24 performances of the Bach prelude. Spectrum analysis of the note samples revealed the relative strengths of harmonic partials in each tone. By comparing the harmonic spectra of the samples, we were able to make some objective claims about string timbre; for example, one string is brighter than another. The harmonic frequency analysis and the recorded performances of Bach will be useful to the violist interested in comparing strings.

Supplementary files included:

- Recordings of individual notes
- Recordings of Prelude from *Suite No. 1* by J.S. Bach
- AutoHotKey script to extract spectrogram data from all audio samples
- Java source code for aggregating harmonic spectrum data
- Spreadsheet with raw output of Java program

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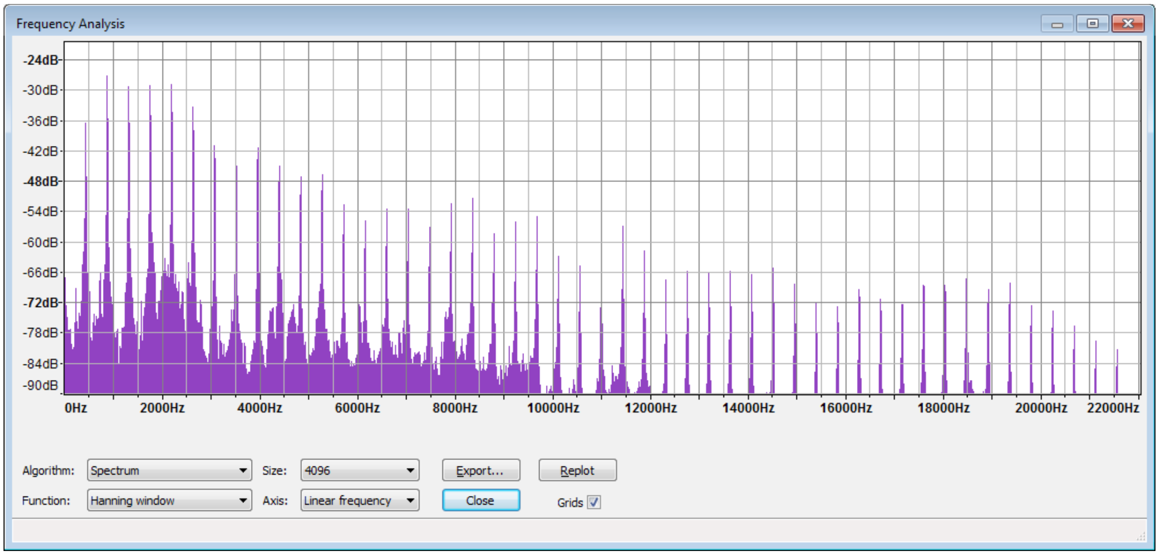
Chapter 1. Introduction

A violist today can choose from dozens of brands of strings. Selection is important because strings can greatly affect the sound produced in performance. Strings may be gut, steel, or synthetic, and their composition influences timbre, playability, and tuning stability. Unfortunately, trying a variety of strings can be prohibitively expensive for a student or professional, and without experimentation it is difficult to form a frame of reference for evaluating strings. Most currently available comparisons of strings are highly subjective and use metaphors that are not easily quantifiable. Any violist who has not had the opportunity to form his or her own opinions from direct experience cannot make an informed decision. Investigation is needed to find a better starting point for musicians interested in trying different strings.

This study compares 12 major viola string brands, combining play testing, recording, and harmonic frequency analysis. Testing was performed on four instruments, since the resonance qualities of individual instruments can affect timbre. We recorded sample notes on each string and instrument combination. Then we measured the frequency spectra of each sample with software. String harmonics appear as evenly-spaced peaks in the frequency spectrum, where peak levels represent harmonic intensities and thus tone quality.



Example 1. Spectrogram of a viola tone. Spikes are harmonics.

Major factors that affect the color of a sound from a string include the string composition and tension, the instrument used, sympathetic vibrations from other strings, bow speed, bow pressure, and contact point. Some of these are easily controlled—sympathetic vibrations can be dampened with felt, a technique used by piano tuners. Other variables, such as bow pressure and contact point, are more difficult to fix, but human performers are practiced in bow control. We chose not to introduce a mechanical playing device, like a monochord. Since the recordings were produced by a human performer, the physical response of the string was a factor in performance, as it would be in a real situation. The human element and variability of instruments complicates the study of strings; nonetheless, we strived for an objective approach, to produce the most rigorous comparison of viola strings to date.

Generating a spectrogram from a single sample is relatively straightforward. With the hundreds of samples taken for this study, evaluating all of them individually was impractical. Instead, a short computer program was written to average spectral data together. Our work produced graphs showing which harmonics are relatively stronger or weaker in different strings. These graphs can be used to make a few objective statements about strings. For example, some strings are demonstrably "brighter" than others, and not all string sets are equally well-blended in timbre. Bright strings produce strong high harmonics, which are observable on spectrograms. This study does not include a detailed statistical analysis; our pool of strings is too small to make strong statistical assertions. Instead, we took several samples from each string (see chapter 4 for details) and averaged the results from different instruments. The goal was to introduce some objectivity in to the process of selecting viola strings.

In addition to the short samples and spectral analysis, this study includes a catalog of characteristic recordings of a Bach prelude. The complexity of a recording of "real music" makes it impossible to perform the same kind of spectral analysis as we did for single notes with any kind of consistency. But musicians may be interested to hear how the strings sound in a performance under the hand of a particular violist. The prelude was performed with every string set on two violas, for a total of 24 recordings.

While many researchers have used frequency analysis to examine sound recordings for various reasons, none have applied it to the comparison of strings in the viola family. In fact, though violins have been evaluated acoustically, the literature does not include comparisons of specific string brands. Previously, string players were forced to rely on personal experience and word-of-mouth information in the absence of any published research comparing the qualities of strings. This study is a first step towards filling that gap.

String choice will always be subject to personal taste, but this work will provide violists with a more objective reference. The violist who is interested in trying new strings will be able to listen to the recordings, form his or her own opinions, and understand in a quantifiable way why one brand sounds different from another—without spending hundreds of dollars to try different strings. Experimentation will always be necessary, since strings may be well suited for some instruments and not others, but our research should benefit musicians looking for a particular sound.

1.1. Outline

Chapter 2 covers background and some previous research in acoustics, psychoacoustics, the study of timbre, and related topics from a physical perspective. We discuss factors that influence timbre, the properties of a vibrating string, and the basics of harmonic frequency analysis. In chapter 3, we approach the study of strings from a musician's perspective, looking at information provided by string makers and various reviews of strings. Methodology is presented in chapter 4, with a detailed description of the recording and analysis process. We describe how free software and our own simple programs aided recording and analysis. Results are presented and discussed in chapter 5.

Chapter 2. Acoustics and Timbre

Sound waves are fluctuations in pressure. Random changes in pressure are *noise*, while periodic fluctuations are perceived as having pitch (Taylor and Campbell 2011). The simplest kind of wave is a sine wave, where a shorter period—higher frequency—results in a higher pitch. Complex vibrations can be periodic but exhibit different wave shapes, including jagged or nearly square waves. Remarkably, Joseph Fourier showed that any complex wave can be described as the sum of a series of simple sine waves called *partials* (Campbell and Greated 1987, 18; Plomp 2002, 16). The lowest frequency in the sum is the *fundamental* frequency of the sound, and is the same as the frequency of the complex wave shape. Other frequencies in the sum are called *overtones*. When the complex wave is periodic, regardless of its shape, its periodic frequency is its fundamental and the frequencies of all component waves in the series are integer multiples of the fundamental (Oldham et al. 2011). For a fundamental f, the frequencies f, $2f$, $3f$, $4f$, etc. are harmonics of f. These frequencies are known to musicians as the harmonic series of f, which includes musically important intervals like the octave, fifth, major third, and so on.

Since a complex sound may be the sum of waves at different frequencies, it is useful to describe the relative strengths of the frequencies in the sound by listing the amplitudes or intensities of each frequency in a frequency spectrum. A graph of a frequency spectrum is a spectrogram, which shows intensity on one axis against frequency on another (and to show spectrum change over time, a 3-D spectrogram adds a time axis, though this is not used in the present study). When only the harmonics are of interest, a frequency spectrum can be reduced to a harmonic spectrum by including only the peak values, showing the intensities of the harmonic frequencies (Campbell and Greated 1987, 20).

2.1. Timbre

Timbre is more difficult to define than other musically relevant attributes of sound. Phrases like "sound quality" or "tone color" are often employed to describe timbre. Pitch and loudness are closely linked to sound wave frequency and amplitude, respectively, although the correlation is not perfect. For example, extreme loudness can affect pitch (Wever 1949, 341). On the other hand, timbre depends on the entire frequency spectrum of a wave. The relative strengths of the component frequencies in a complex tone result in a characteristically shaped frequency spectrum. In many musical situations, the components of a tone are harmonic, so only the harmonic spectrum is needed to describe timbre. Unlike pitch or loudness, which are each single-dimension attributes—either "high" or "low"—timbre is multi-dimensional (Wedin 1972, 228), since it depends on multiple frequency components that can vary independently. But a complete record of the harmonic spectrum is not needed to describe timbre, because some seemingly disparate spectra can generate the same timbral sensation (Campbell and Greated 1987, 145). Though musicians use many words to describe timbre, like "warm," "bright," "rough," "clear," "sharp," etc., research has shown that three or four dimensions may suffice, as with visual color (Campbell and Greated 1987, 148; Wedin 1972, 239). Verbal descriptions are difficult to quantify, with a few exceptions: "bright" or "sharp" usually means strong in upper harmonics and "nasal" or "hollow" can mean stronger in odd-numbered harmonics (Campbell and Greated 1987, 151; Caclin 2008, 53). Factors other than the shape of the harmonic spectrum that may influence timbre are discussed below.

Timbre is known to depend on the frequency spectrum of a sound, but the importance of the phase is less clear. Phase is the time displacement of one frequency component relative to another; for example, the second harmonic wave may begin at the same moment as the fundamental or may be displaced by a fraction of a cycle. Different phase relationships result in different composite waveforms that may have the same frequency components at the same relative amplitudes. Some researchers have found evidence that phase affects timbre (Wever 1949, 420; Patterson 1987, 170), but many others have found that the ear cannot detect phase or that phase changes are not significant in realistic settings (Wever 1949, 419; Risset and Wessel 1999, 114; Campbell and Greated 1987, 19). In a normal, reverberant environment, phases are obscured: sound waves are reflected so that the phases of components reaching the listener are unpredictable, but this does not seem to prevent listeners from having a unified perception of timbre, so phase cannot be very important in this setting (Plomp 2002, 19; Risset and Wessel 1999, 141). The recordings for our research were made in a reverberant room, so phase could be safely ignored.

Inharmonicity of overtones can affect timbre and pitch. A mistuned low harmonic in a complex tone causes the perceived pitch to shift, within a small tolerance; when the intonation is distorted enough, the mistuned harmonic is heard as a separate component (Moore 1987, 180). Inharmonicity can add "warmth" to a sound, and can affect the timbre of instruments like the piano where the natural stiffness in a struck string results in mistuned harmonics (Järveläinen et al. 2001, 79). But the harmonics of a bowed string, unlike a plucked or struck one, cannot be out of tune (Oldham et al. 2011).

Our research centered on the timbral differences of bowed strings, so string harmonics were never out of tune.

The onset of a sound may be markedly different from the rest of the tone. Frequency components that are present only for the initial attack of a tone are called *transients*. Similarity of timbre between two tones depends primarily on shapes of their harmonic spectra after the transients have disappeared. Instrument identification, however, often relies on transients and is a higher cognitive function than sensation of tone quality (Roederer 1995, 151). The brain appears to possess two types of timbre perception: one which considers only sustained spectral distribution and another which includes attack transients, where the former distinguishes sounds from the same instrument family and the latter can associate sounds with different families (Risset 1999, 157). Transients are also important for different types of bow attack: slurred, spiccato, etc. Since our work involved comparing the sounds of viola strings, we used only smooth bow strokes and ignored the attack sounds, focusing instead on the spectra of sustained tones.

A bowed string may produce over 40 harmonics in the range of human hearing. These harmonics are visible on a spectrogram as equally-spaced spikes. But the ear is only capable of individually resolving the first seven or so harmonics; higher ones tend to blur with neighboring harmonics (Roederer 1995, 122). The first few harmonics are also generally the loudest. Higher harmonics are perceived, but they are heard collectively as a single perceptive component called the *residue* (Warren 2008, 76). The residue is important in determining pitch and timbre. The ear can correctly infer the pitch of a complex tone with fundamental 200 Hz even when the first ten harmonics are missing, though the timbre will be different than if the lower harmonics were present (Warren 2008, 85). Thus when comparing spectrograms regarding timbral attributes, we include data from many harmonics but must be careful to give proper emphasis to the lower ones, which are individually perceptible. The set of higher harmonics should be considered as a fused attribute, as the listener will hear it as a single entity and be unable to distinguish its components individually. Nonetheless, this attribute is still an important factor in timbre, as it affects the "brightness" of a sound.

Since the shape of the harmonic spectrum above a fundamental determines the timbre of a tone, and we typically perceive pitch as a relative attribute, it is tempting to think that the same spectral shape can be shifted up or down in frequency without affecting timbre. In fact, even a simple sine wave appears to change in quality over the range of audible frequencies (Risset 1999, 115). Keeping timbre constant while varying fundamental pitch is slightly more complicated than it seems at first glance. The ear listens for the intensities of harmonics in certain absolute ranges to gauge timbre. A region of peak harmonic intensity is called a *formant* (Campbell and Greated 1987, 154). For example, a violin may resonate in a way that causes harmonics in a certain range to be louder, regardless of which note the performer is playing. In fact, violins may have as many as 20 or more resonance peaks within the range of human hearing, creating a characteristic timbre across the range of the instrument (Risset 1999, 129). Formants are important for identifying timbre when the fundamental changes. They are relevant when comparing tones of different pitch, or when comparing instruments with different response curves, as acousticians have done (McLennan). String instrument response curves are highly complex due to irregular body shape; some research has examined the resonance properties of violins with various geometric imaging tools (Bissinger and Oliver). Violin and viola response curves are quite different; principal resonances on a viola are 20-40% lower than the violin, and air and main body resonances are *between* open string frequencies instead of *at* them (Fletcher and Rossing 1998, 318). Since our research concerns the comparison of strings, we averaged data from four different violas to avoid biasing our spectrograms with the resonance curve of a single instrument. As long as we compare strings at the same pitch, formants will affect the spectra equally and not interfere with a harmonic spectrum analysis.

2.2. String Vibration

The vibration in a string instrument is initiated by either plucking or bowing a string, where each action results in a different type of vibration. When a string is plucked, two displacement waves travel in opposite directions from the point of excitation (Fletcher and Rossing 1998, 42) and are reflected at the ends of the string (Fletcher and Rossing 1998, 38). Since waves are traveling in both directions on the string, they will quickly overlap and interfere. The interference produces *standing waves* that do not travel the length of the string. Standing waves are the only possible stable vibration that can appear in a string with fixed ends (Roederer 1995, 107). The standing waves in a string vibrate in multiple harmonically related modes (Campbell and Greated 1987, 192). So it is the reflection of waves at string ends and the resulting harmonic standing waves that produce the timbrally rich sound of a string instrument.

Bowing a string creates a different, but related, kind of motion. As with plucking, bowing causes two waves to travel in opposite directions, but one is quickly dampened by friction of the bow against the string (Fletcher and Rossing 1998, 50). The bow impulse that isn't dampened travels as a sharp corner (bending point) in the string, reflecting at the string ends. As the corner travels, the string alternately sticks and slips against the bow, an effect called Helmholtz motion (Fletcher and Rossing 1998, 47). Because the corner travels very fast and displaces the string more near the middle, the string motion appears to the eye to blur into a sharpened, elongated oval.

Marin Mersenne first discovered the factors that affect string pitch in 1636: frequency is inversely proportional to string length and the square root of its mass, but proportional to the square root of tension (Wood 1975, 44). Other factors can affect the sound of a string, especially stiffness. An ideal string is perfectly flexible, but a real one is somewhat stiff, which has different effects on plucked and bowed notes. The harmonics of a plucked note are more out of tune for stiffer strings; bowing forces the harmonics to be in tune, but stiffness in the string affects the ease of bowing (Weinreich 2011). Stiffer strings have rounder corners in Helmholtz motion, resulting in "jitter" noise and a tendency for increased bow pressue to affect pitch (Fletcher and Rossing 1998, 280). Stiffness and other properties depend on the composition of a string. Strings may be made from metal, gut, or a synthetic polymer. Materials and construction techniques vary; some strings are composed of multiple materials, with one type overwound on a different core (Weinreich 2011). For this study, we selected strings with a variety of compositions and densities to get a broad sample of string types.

A string, once excited, loses energy in several ways. If the string was plucked, energy loss gradually dampens the string until it stops vibrating. A moving bow continues to add energy to the string, keeping the sound relatively constant until the bow is removed or changes direction. There are three types of damping: by air friction, internal damping, and transfer through the ends (Fletcher and Rossing 1998, 53). The damping process is affected by the radius, density, and complex elastic properties of the string. Metal strings tend to lose most of their energy to the air, while gut, synthetic, and composite strings are most affected by internal dampening (Fletcher and Rossing 1998, 54). Some energy must also be transfered to the bridge so that the sound may be amplified and eventually reach listeners. The complexity of interactions in vibrating strings renders them difficult to model physically in a way that allows accurate prediction of sound quality. We should be careful not to overgeneralize about the sounds of various materials; for example, in section 5.3 we find that metal strings can produce bright or dark timbres.

2.3. Spectral Analysis

Spectrograms can plot intensity against frequency, and may include a third axis for time. Without a time axis, a spectrogram represents a spectrum snapshot from a sample. But it may be useful to take an average of all spectral data from a recording. A graph of this kind is called a long-time-average-spectrum (LTAS) and is common in acoustics research (Campbell 1987, 155). A LTAS will also average out fluctuations in harmonics caused by minute changes in position relative to the microphone or changes in sound production by the player. This represents a more realistic picture of what a listener hears, since when a listener's head moves slightly, the brain smooths out slight changes in timbre information to produce a unified impression of tone color (Campbell 1987, 147). Our research uses LTAS to represent sound quality in a two-dimensional plot.

Generation of spectrograms and LTAS can be accomplished with a variety of software tools, many of which are free. Several free solutions exist:

- *Audacity* is software primarily used for sound recording and editing, but now includes spectrogram plotting functions. The user interface is intuitive and straight-forward; almost no background knowledge is needed to record a sample and display its frequency spectrum.
- *WaveSurfer* is a more powerful analysis tool, originally developed for speech research. It can display formants as well as spectra and currently offers more configuration options than Audacity. However, the interface uses many abbreviations and jargon, making it slightly less friendly for non-acousiticians.
- *Sonogram* is another analysis tool, offering flexibility similar to WaveSurfer. ("Sonogram" is a synonym for "spectrogram.") One distinguishing feature of this software is its use of the Java3D API to display attractive 3-D spectrograms.
- *E-Synth* can analyze or synthesize sounds. For clean, short samples, it is able to find the harmonic spectrum by detecting the fundamental, and it allows the user to modify the intensities and phases of individual harmonics. E-Synth is easy to use. It proved less useful for our work, where samples include attack noise that seemed to interfere with its analysis.

Other programs are available with varying degrees of sophistication. We used Audacity because it includes both recording and basic analysis functions.

Many researchers have used spectral analysis on musical tones. Alm and Walker show how spectrograms can differentiate between the tone colors of piano, flute, and guitar tones (2002). Mottola used spectrograms to analyze the aural effects of different electric bass guitar components (2002). He compared the spectra generated by two different types of bass guitar strings. Jansson used LTAS to measure violin timbre in various conditions (2002). Yasuda and Hama compare bass guitars by analyzing the formant structure of spectra produced from recordings (2007). Gunawan and Sen explored the relationship of frequency to spectrum discrimination; they found that for different pitches, the sensitivity of the ear to changes in harmonic spectrum changes (2008, 506). Christiansen analyzed the timbre of sung vowels, comparing frequency spectrum and tone quality as perceived by a jury of professional musicians (1988). None of these examples, however, apply spectral analysis to strings in the viola family.

Chapter 3. Strings

The previous chapter discussed some of the factors that can influence the sound of a string from an acoustical perspective. The precise sonic effect of different string constructions can be difficult to measure, so there has been little published research comparing strings. Presumably, string makers do some work of this kind, but none of the makers contacted for this study (including the makers of each brand of string tested; see section 4.1) were able to provide any research beyond basic data on string tensions—an understandable result of needing to protect trade secrets. On the other hand, musicians often have strong opinions about strings based on their own experiences. Subjective evaluations are colored by the instrument used to test a string (since instruments have varying response curves) and by the personal taste of the musician making the evaluation. An ideal sociological solution would be to have a large group of musicians try out different strings on the same instruments, gathering the opinions of the group and looking for statistical trends. But acquiring a significant sample size and preventing bias would be difficult.

No extensive, rigorous study like this is currently available, but there are reviews by individuals on the internet and marketing material published by string makers. We examine some of this material, keeping in mind the limitations and probable bias of prose evaluations. We also list, for reference, publicly available technical data on the strings used in our research.

3.1. Technical Data

Information on string composition and tension is taken from the maker's website, when it is provided, or else from e-mail correspondence with the string maker or the Shar catalog. Tensions were provided in various units, but have all been converted to Newtons (the SI unit of force) for comparison. Most strings were tuned up and measured at a vibrating length of 370 mm, but some makers used slightly different lengths, which are also noted. Jargar Strings ApS and Pirastro GmbH declined to provide tension data for this study.

String composition and tension data

	mm	Core / Winding	N	Core / Winding	N	Core / Winding	N	Core / Winding	N
String Set (medium gauge)	**Length**	**A material**	**Tension**	**D material**	**Tension**	**G material**	**Tension**	**C material**	**Tension**
1. D'Addario Helicore	380	Steel rope / Aluminum	75.6	Steel rope / Titanium	56.9	Steel rope / Silver	61.4	Steel rope / Tungsten-silver	58.3
2. D'Addario Zyex	380	Synthetic / Aluminum	70.7	Synthetic / Titanium	52.5	Synthetic / Silver	52.5	Synthetic / Tungsten-silver	50.7
3. Jargar		Steel / Chromium		Steel / Chromium		Steel / Chromium		Steel / Chromium	
4. Larsen	370	Steel / Alloy	83.1	Synthetic / Alloy	48.4	Synthetic / Silver	48.6	Synthetic / Silver	49.1
5. Pirastro Eudoxa	370	Gut / Aluminum		Gut / Aluminum		Gut / Aluminum		Gut / Silver	
6. Pirastro Evah Pirazzi	370	Steel / Chromium		Synthetic / Silver		Synthetic / Silver		Synthetic / Tungsten	
7. Pirastro Obligato	370	Synthetic / Aluminum		Synthetic / Silver		Synthetic / Silver		Synthetic / Tungsten-silver	
8. Pirastro Tonica	370	Synthetic / Aluminum		Synthetic / Aluminum		Synthetic / Silver		Synthetic / Silver	
9. Super Sensitive Red Label	369	Steel / Nickel	86.7	Steel / Nickel	75.6	Steel / Nickel	65.4	Steel / Nickel	48.5
10. Thomastik Dominant	370	Synthetic / Aluminum	58.7	Synthetic / Aluminum	48.9	Synthetic / Silver	47.1	Synthetic / Silver	48
11. Thomastik Spirocore	370	Steel rope / Chromium	78.3	Steel rope / Chromium	69.8	Steel rope / Chromium	66.7	Steel rope / Chromium	62.7
12. Thomastik Vision	370	Steel / Chromium	80	Synthetic / Silver	55.6	Synthetic / Silver	54.7	Synthetic / Tungsten-silver	53.8

3.2. Advertised String Properties

The following quotes are taken from string makers' websites. They are presented here for comparison, then discussed below. Keywords are emphasized here (not in the sources).

1. D'Addario Helicore—"Helicore viola strings are crafted with a multi-stranded steel core, making for optimum **playability** and producing a **clear**, **warm** tone. The smaller string diameter provides **quick bow response**. Premium quality materials combine with skilled workmanship to craft strings with excellent pitch **stability** and **longevity**."
2. D'Addario Zyex—"Zyex synthetic core strings produce an extremely **warm**, **rich** sound. Zyex is a new generation of synthetic material, creating strings that are extremely **stable** under drastic climatic conditions. Zyex strings **settle in on the instrument very fast**, within a matter of hours. Zyex has a **warmer** sound than most other synthetic core strings, making them excellent for use on brighter sounding instruments."
3. Jargar—"The production of Jargar viola strings is based on a special, flexible steel core, like the violin strings. All viola strings—A, D, G, and C—are wound with thin threads of metal—aluminum, copper, and different alloys. The strings produce a **big**, **powerful**, **distinct** and **well-balanced** tone."
4. Larsen—"A unique concept of wire core and winding technique has brought the new Larsen Cello Strings G and C as close as at all possible to the musical **virtues of the classical gut string**. [. . .] With its new Cello G and C medium strings, Larsen Strings has once again succeeded in further developing the exclusive

musical qualities of the classic gut string. With a unique wire core at their heart, the new strings offer the qualities that soloists, orchestral players and chamber musicians have long been searching for: Great **strength** and **volume**. **Deep**, **beautiful sonority** with a **distinct clarity**. A **clear attack** and an **immediate response**. In fact, their response is as immediate as Larsen's internationally renowned Cello A and D strings. Taken together, this complete set of cello strings sets new global standards for **blend** and **evenness**." (Note that at this time, the Larsen website makes no claims about their violin or viola strings as distinct from cello strings. Their original product was the cello string set.)

5. Pirastro Eudoxa (gut core)—"Excellent **warm** sound which offers a high ability of **modulation**; **quickly tuned**; per 1/4 PM the tension alters by 3%."
6. Pirastro Evah Pirazzi—"The **power** string: very **intensive** and powerful; **brilliant** and **complex** sound; **widest dynamic range**; emphasize the individual sound picture of each instrument; outstanding response; **immediately playable**; perfect **set harmony**; **resistant to changes** in temperature and humidity."
7. Pirastro Obligato—"The allround synthetic core string; **warm** and **brilliant** sound; **big** and **powerful** volume; **easy response**; **immediately playable**; perfect **set harmony**; **resistant to changes** in temperature and humidity."
8. Pirastro Tonica—"**Soft**, **round** and wide range of **modulation**; **big** volume; **easy response**; **not sensitive** to humidity; **immediately tuned**; **powerful brilliant** sound."
9. Super Sensitive Red Label—"Recommended by a wide range of orchestra directors and studio teachers worldwide; full round solid steel core string with flat

nickel winding; provides **excellent tonal quality** with a high degree of tuning **stability**; **economical** and **durable**."

10. Thomastik Dominant—"**Comparable in sound to gut**, without gut's disadvantages. These strings have a highly flexible, multi-strand nylon core and cater for artists who feel uncomfortable with steel strings. The resounding success of our Dominant string owes a lot to its similarity in tone and response to gut strings, without gut's attendant drawbacks. The sound of the Dominant string is **full** and **mellow**, yet **rich** in overtones. Its **radiance**, its **ability to project** sound without being metallic, comes to the fore both in arco and pizzicato. Other advantages are Dominant's effortless **response to intricate fingering** and its tuning **stability** even under extreme atmospheric conditions. But Dominant's beauty of tone is **not as long lasting** as that of a steel string, a price the discerning musician will be prepared to pay for this quality of sound. Dominant strings should be changed at appropriate intervals to ensure continuity of tone color."
11. Thomastik Spirocore—"Hi-tech, top grade, spiral steel core strings. Spirocore strings are a further technical development of our Künstler Seil series and have a flexible spiral steel core. This core has greater **elasticity** than that of conventional strings, which means less inertia and a higher propensity to musical vibration. The sound is **full** and **homogenous**, **balanced** and **voluminous**. The string has been calibrated to satisfy the express wish of many artists for an equally effective arco and pizzicato. [. . .] Spirocore's hi-tech core makes for **effortless fingering**, **responsive bowing**, **stable** tuning and a very **long string life**."
12. Thomastik Vision—"These strings are specifically designed to fulfill the needs of

advanced violinists, including those who excel in **orchestral or chamber group settings**. They **settle in quickly** and can achieve a **stable** tuning within a very short time and are exceptionally easy to play. Their **durability** is unsurpassed compared to other synthetic core strings. Players will be pleased with the **compatibility** between Vision™ strings and other Thomastik-Infeld synthetic core strings such as Dominant™, Infeld™ Red and Blue."

3.3. Discussion

Words and phrases describing strings can be grouped by similarity and according to whether they make claims about sound or some other attribute. The tables below summarize the types of claims made in the advertisements.

<u>Sound</u>

- clear sound or attack
- warm, mellow vs. brilliant, radiant
- powerful, strong, big, intensive, voluminous, projecting vs. soft
- well-balanced, full, deep, complex, rich
- blend, evenness, compatibility, set harmony, homogeneity
- dynamic range, modulation
- suitability for solo vs. orchestra / chamber
- similarity to gut
- beauty or excellence of tone

<u>Other</u>

- settling / break-in time
- tuning stability
- economy
- durability, longevity
- bow or fingering response
- elasticity

Reviews of strings use similar words. Of the words referring to sound, some are more clear than others. "Beauty" or "excellence of tone" are highly subjective terms. Words referring directly to timbre are more quantifiable; "brilliant" or "bright" sounds tend to be strong in the upper harmonics, while "warm" or "mellow" sounds emphasize the lower harmonics. "Full," "rich," or "well-balanced" tends to mean that a sound has a mixture of lower and upper harmonics and is not weak in any particular range. Terms like "compatibility" and "set harmony" mean that the strings match well with each other. This can mean that the sounds of the strings in a set blend well or that they play well together. Using strings from a single set, where the tensions and compositions have been deliberately matched, can make for easier bow response. Note that the tensions in a matched string set are not identical, but they tend to "feel" the same (Peruffo).

In any case, not all of the descriptions use words consistently. The Obligato advertisement promises both a "warm and brilliant" sound, which appears to be a contradiction, given the way that others use those words. Dominant offers a "full," "mellow," "rich," and "radiant" sound. Tonica is "soft," "round," "powerful," and "brilliant." One common feature in both advertisements and reviews is a generally accepted preference for the sound of gut strings. Descriptions of synthetic strings often claim that they reproduce the "sound of gut" without the issues of tuning stability and sensitivity to the weather.

3.4. String Reviews

Several string reviews are available on the internet, but the reader must use caution in evaluating them. Many of them appear to borrow from others, in some cases using the same words, so it is unlikely that each represents a totally independent comparison. The *Strings Magazine* article by Richard Ward, "Find your sound," appears to be a source for parts of many of the other articles, though with incomplete bibliographies in many it is difficult to tell which source is the original. Some of them were probably influenced by the marketing material published by the string makers. However, the reviews also contradict each other and the advertisements in some cases, so it is still worth comparing them.

There is a basic consensus on the three major string types.

- Gut: Full, complex sound (Ward), warm and rich (Violinist.com, Ifshin), but lacks in tuning stability (Johnson, Roche, StringMail) and takes longer to setlle in (Ward; Fletcher and Rossing 1998, 284).
- Steel: Clear, direct, pure, not complex (Ifshin), tending towards brightness though not always (Ward), can be thin-sounding (Johnson, Violinist.com), but extremely stable (Ward; Fletcher and Rossing 1998, 284).
- Synthetic: Full, rich (Johnson), supposed to sound like gut without the stability problems (Violinist.com, Ward). Sometimes described as warm (Violinist.com) or bright and not quite reaching the quality of gut (StringMail).

Gut strings have the most desirable sound, usually described as warm and rich, but are more difficult to handle. Metal strings provide projection, clarity, and often brightness, but tend to sound different from (and not always "as good as") gut. Synthetic strings are supposed to compromise between the sound of gut and a higher stability. Sources disagree on how well synthetic strings imitate the sound of gut and whether the sound is warm or brilliant. Below, we compare what reviewers had to say about string brands. A phrase with multiple citations indicates that different sources used the same or similar words, agreeing on some feature of the strings.

1. D'Addario Helicore—"warm," which is "unusual for a steel-core string" (Johnson,

Ifshin), "warm" and "smooth" (Ward), "very responsive" (Violinist.com).

2. D'Addario Zyex—loud, "powerful," "pure" (Westbury Park), "bright, focused quality" (Violinist.com, Ward). This is intriguing, since the maker advertises Zyex as having a "warm, rich" sound, which would seem to be the opposite.
3. Jargar—"warm" (Ward, Violinist.com, Johnson Strings). Not many comments about this string set, and the agreement on "warmth" seems to contradict the advertisement of a "big, powerful, distinct and well-balanced tone."
4. Larsen—"pure, clear sound" (Johnson), "brilliant" but not as much as Dominant (Ifshin), "powerful and brilliant" (Ward), more powerful than Dominant (Violinist.com). The reviews seem to agree that the strings are powerful, but none of them compares Larsen directly to the sound of gut as the maker did.
5. Pirastro Eudoxa (gut core)—"dark, warm, and quite full" (Ward), "rich, warm, and quite full" with slower response, sometimes "dull" (Violinist.com), "warm, mellow" (Ifshin), "beautiful," "refined," "warm" sound (Westbury Park).
6. Pirastro Evah Pirazzi—soloist strings, "powerful," "bright" (Westbury Park), "brilliant" (Ifshin, Ward), "powerful," "full, round sound" with good "range" (Violinist.com). Like Pirastro, reviews tend to emphasize the power and brilliance of these strings. One review said it is difficult to achieve an "intimate" sound (Westbury Park).
7. Pirastro Obligato—seen as a good synthetic substitute for Eudoxa gut strings (Ifshin, Westbury Park, Ward, Violinist.com), "more responsive and more brilliant than gut" (Violinist.com).
8. Pirastro Tonica—similar to Dominant, slightly "more complexity" (Violinist.com,

Ward), "slightly warmer and fuller than Dominant" (Ifshin), "brilliant like the Dominants" but "fuller" than Dominant (Johnson). All of the reviews try to find some small difference from Dominant (and they come to somewhat contradictory conclusions), but they seem to agree that the strings are very similar.

9. Super Sensitive Red Label—low cost and durability are the most commonly cited features (Johnson, Ifshin, Ward), while one reviewer frankly complained about Red Label's "plain, brittle, harsh" sound (Violinist.com). None of the reviews mentioned here praised the strings for their "tonal quality," as the maker does.
10. Thomastik Dominant—"full and mellow" sound, which some people compare to gut, although others disagree (Violinist.com), "brilliant and responsive" (Ward), "bright and responsive" (Ifshin, Johnson), "warm" and "round" (Westbury Park), has a metallic edge that fades after a few days (Johnson). The last claim reiterates the need to let strings settle before evaluating their sound.
11. Thomastik Spirocore—"bright," with "edge" (Johnson, Ifshin, Ward). This common description is in conflict with the maker's claim to a "full" and "balanced" sound.
12. Thomastik Vision—stable, easy to play, settle quickly (Violinist.com), with "brilliance and focus" like Dominant but with "more character" (Ifshin). The last comment was the only one to mention the sound of Vision strings, and the maker also says very little about their sound.

We summarize the adjectives that reviewers used in a table. The descriptors that appear to be related to "brightness" are grouped together and ordered (subjectively, by this author) from dark to bright. The table is partly an oversimplification, but it illustrates how in some cases reviewers have failed to agree on even the most basic aspects of timbre: consider, for example, the contradictory assessments of Tonica and Dominant brands.

String Set (medium gauge)	1. D'Addario Helicore	2. D'Addario Zyex	3. Jargar	4. Larsen	5. Pirastro Eudoxa	6. Pirastro Evah Pirazzi	7. Pirastro Obligato	8. Pirastro Tonica	9. Super Sensitive Red Label	10. Thomastik Dominant	11. Thomastik Spirocore	12. Thomastik Vision
Brightness spectrum:												
dull					X							
dark					X							
warm	X		X		X			X		X		
mellow					X					X		
smooth	X											
full					X	X		X		X		
rich					X							
clear				X								
pure		X		X								
focused		X										X
bright		X				X				X	X	
brilliant				X		X	X	X		X		X
Other descriptors:												
responsive	X						X			X		
powerful		X		X		X						
refined					X							
round						X				X		
range of sound						X						
complexity								X				
harsh									X			
brittle									X			
plain									X			
edge											X	

Summary of descriptors used in reviews of strings

3.5. The *String Study* Product

One violin shop (Williams Fine Violins & Luthier Studios) has made a special effort to help violinists compare strings. *String Study* is a 2-CD set of recordings made with 57 different sets of violin strings. The CD set is a commercial product offered on its own, without any commentary by the creators on the strings. Thus it is in a different class from the reviews and advertisements described in the previous sections. The recordings are all made with medium gauge strings, on two violins, by two different violinists, with two microphones. One of the violins is a modern Chinese one, and the other is an older German instrument. Each recording is a set of scales. The purpose of *String Study* is to let violinists hear and judge strings for themselves. However, it does have limitations, described below, which are addressed in the present research.

The strings were played "right out of the box," without any time to settle. Some string types are known to settle more quickly than others (Fletcher and Rossing 1998, 284), and for most strings, it is unlikely that the "out of the box" string sound represents a typical sound over the life of a string. The scope of *String Study*, with 57 different string brands, likely precluded allowing any time for breaking in the strings. Our research allowed two weeks for each string set to stretch and settle. Also, the method described does not mention any special restrictions on how the strings were played. For example, the authors do not specify whether neighboring strings were muted during the recordings, suggesting that they were allowed to resonate sympathetically. If this is true, the sound of each string would be affected by adjacent strings. For the present study, strings not in use were muted with felt to avoid this problem. Although the recordings are scales, rather than pieces, the study's method tends to suggest a "realistic" approach was taken, allowing more variation in human playing to affect the sound. Our own study of viola strings includes Bach recordings that take this approach to allow the listener to judge strings in a musical context, while our focus in acoustic analysis is on recordings of individual notes with more carefully controlled conditions. Certainly, the world of string players can only benefit from more recordings like these.

Chapter 4. Method

The present study involves comparing timbres of viola strings; since tone quality is such a volatile feature of sound, we were careful to control as many variables as possible during the recording process, as we discuss in section 4.2. The recording process produced hundreds of samples, far too many to analyze individually, so we constructed simple computer programs to aggregate the data. This chapter describes the materials used and process followed to produce and analyze recordings of strings.

4.1. Materials

The twelve string sets selected for this study were chosen to include popular brands and different types of strings. All strings are medium gauge, full size (for 16"+ violas). Strings were purchased from a catalogue (not provided by the makers), to avoid introducing bias.

1. D'Addario Helicore
2. D'Addario Zyex
3. Jargar
4. Larsen
5. Pirastro Eudoxa (gut core)
6. Pirastro Evah Pirazzi
7. Pirastro Obligato
8. Pirastro Tonica
9. Super Sensitive Red Label
10. Thomastik Dominant
11. Thomastik Spirocore
12. Thomastik Vision

We used four violas for this study, varying in quality from student to professional grade instruments. For analysis, we averaged sample spectrum values from all four instruments, reducing the impact of the individual resonance curve of each viola.

1. 16½": Wilhelm Klier, 1999.
2. 16½", Tertis model (wide body): Andreas Eastman, 2004.

3. 16": Rudoulf Doetch, unknown year.
4. 16¼": Stanley Kiernoziak, workshop of William Harris Lee, Chicago, 2002.

The bow is stamped Alfred Knoll. The same bow was used for all of the recordings. During the recording process, the bow was rosined lightly at frequent intervals to keep the amount of rosin as consistent as possible.

New strings need time to stretch out. The sounding frequency of a string tends to fall after it is first tuned, with break-in time depending on the composition of the string: steel stabilizes within a few minutes, while synthetic strings take about 8 hours, and gut take 48 hours (Fletcher and Rossing 1998, 284). Experience suggests that these times are conservative, and some strings may require several days to fully stabilize. We allowed two weeks for each set of strings to settle. With four violas and twelve string sets, we were able to install a third of the strings at a time. During the break-in periods, the instruments were tuned and played regularly. All of the materials were kept in the same room at a contant temperature of 21° C, and humidity was typically 30%-45%. Once the strings had a chance to stretch, they required no additional time to adjust to different violas. Changing a set of strings from one instrument to another did not negatively affect stability.

4.2. Recording

Recordings were made in a moderately reverberant room. Some reverberation is desirable, since it is expected in a performance space, and the recording will capture a more "average" snapshot of the sound (reducing the importance of the location of the microphone and sound source). Too much reverberation can distort the recorded frequency spectra, since a rectangular room will itself have a resonance curve. An ideal room for measuring the timbral properties of instruments or strings would be a reverberation chamber, a large room where no walls are parallel and walls are especially sound reflective. The absence of parallel walls prevents standing waves, dispersing sound approximately equally throughout the room. (Campbell and Greated 1987, 545) Unfortunately, no such room was available. We compromised with a room that was not acoustically dead, but also not obtrusively reverberant.

The microphone was a Blue Snowflake, which has a cardiod polar pattern. It was positioned about 1 m from the viola, at the same height for each recording. The Snowflake responds to frequencies in the range 35 Hz – 20 kHz, which includes the lowest viola string frequency to the upper end of the audible spectrum. Recordings were sampled at 44.1 kHz. The viola and microphone were placed in the same absolute positions within the room for each recording. When one string was recorded, other strings were dampened with pieces of felt between the strings and fingerboard, much as a piano tuner does to avoid the confounding effect of sympathetic vibrations.

Common factors manipulated by string players to affect tone include bow speed, contact point, angle, and pressure. Bow speed was the easiest thing to fix: a silent, blinking metronome set to 60 beats per minute allowed fairly precise control over timing. Pieces of tape on the bow marked the limits of bow to be used, 4 cm from each end of the hair, and the midpoint of the bow to increase timing precision. Each sample included four consecutive bow strokes of 2 seconds each, for a total of 8 seconds per sample. A large mirror allowed visual observation of the first three bow variables, which were controlled manually. A device to completely eliminate the human element and move the bow mechanically would have fixed most of the variables, but such a solution would be arguably less realistic. Instead, this author endeavored to play at a full forte volume, keeping the bow in the "sweet spot" a little less than halfway from the bridge to the fingerboard, and maintaining a constant bow angle. Naturally, strings of varying composition respond to the bow in different ways, musicians may react to the tactile feedback differently, and playing perfectly consistently for hundreds of samples is impossible; nevertheless, every reasonable effort was made to keep the action of the bow fairly constant. We expect that the sample size will be sufficient to mitigate the effect of human performance variability.

Three 8-second samples were recorded for each string and instrument: one with the open string, one a major third above the open string, and one a perfect fifth above. We also recorded the Prelude from the first cello suite by J.S. Bach on instruments 1 and 4 (see above) with each set of strings. The Bach recordings were made for the interested reader's reference; they were not used in the spectral analysis. We selected this work because it is a short, standard piece that uses a wide range of notes on the viola and produces a great deal of resonance in the instrument. Variation among the performances is unavoidable, but they will provide a real record of how the strings can sound on two instruments under the hand of one violist.

We named the sample note files with numbers in the format "1_2_3_4", where each number respectively indexes string set (brand), instrument, string (A, D, G, C), and sample note (open string, M3 above open, P5 above open). Section 4.1 lists the string sets and instruments with the index numbers used in this study. The Bach recordings were named in the format "bach_1_2", indicating string set and instrument.

4.3. Analysis

Recordings and spectrum analysis were performed with Audacity v. 1.3.12-beta.

After selecting the whole sample, the Analyze → Plot Spectrum function plots a LTAS of the sample. This function uses a Fast Fourier Transform (FFT) to plot a spectrogram with specified settings. We used a Hanning window with a block size of 4096. Too low of a block size would cause the harmonic peaks to blur together for lower frequency notes, where the frequencies of harmonics are close together. This size was sufficient to distinguish the harmonic strengths of the lowest sample, the open C string. A spectrum plot can be exported to a plain-text file with a list of frequency-intensity pairs.

The first step in analyis was to plot spectrograms for each of the 576 sample notes. This rather tedious task can be performed by a script, so we used AutoHotkey. For each sample, our script opened the file in Audacity, plotted a spectrogram, and exported the data to a text file. Any missing or empty files would have crashed the script.

With the raw data in text files, a way was needed to aggregate and analyze it in a meaningful way. For this purpose, Java SE v. 6 was used to build a simple program, including JUnit tests of its basic functionality. The goal was to construct two groups of tables: one group of string-set-focused tables, plotting harmonic strength against sample notes, and a group of sample-focused tables, showing harmonic strength against string brand.

Our primary interest is the shape of the harmonic spectrum compared to average values. As previously discussed, the timbre of a sustained tone is largely dependent on the shape of its harmonic spectrum. For each harmonic in each spectrum, we subtracted the average intensity of that harmonic; then we subtracted the difference between that spectrum's fundamental intensity and the average fundamental intensity. This allowed a consistent comparison of string harmonics. Subtracting the fundamental intensity reduced the effect of minor differences in recording volume, so that timbre could be compared more easily.

4.4. Spectrum Analysis Program

The Java program has four classes:

- HarmonicSpectrum—A data class that stores a list of harmonic intensities in double precision. Includes a function to average multiple spectra by taking the mean of each harmonic.
- SpectrogramFileReader—Reads the text files generated by Audacity into HarmonicSpectrum objects. The most significant function here is the interpretation of the frequency spectrum as a harmonic one. Given the approximate frequency of the fundamental, this class computes a window of ±20% around each harmonic and takes the maximum value within that window to be the intensity of the harmonic. This is large enough to ignore minor intonation discrepancies but small enough to avoid interference from neighboring harmonics.
- Table—A data class that prepares a table of numbers for export to CSV (comma-separated values) format, which is readable by any spreadsheet program.
- Analyzer—The main class that averages data from the proper files and outputs the results to a single CSV. The general process is:
    1. Read spectrogram data
    2. Compute averages
    3. Build tables
    4. Output tables to CSV

Methods in the Analyzer class:

- doAnalysis() invokes the other methods and dumps all of the data to a single file.
- readSpectralData() reads the files into an array of HarmonicSpectrum objects.
- averageOverInstrument() averages the spectrum data for each string and sample from all four instruments.
- averageOverStringSet() takes the result from averageOverInstrument() and averages data for each sample from all string sets. These methods provide a baseline for comparing individual samples.
- averageOverSamples() takes the result from averageOverInstrument() and averages data from all sample notes on a single string, creating an average result for each string set and string.
- averageOverString() takes the result from averageOverSamples() and averages data from all string sets, creating a baseline for each string. The result is a spectrum for each of the A, D, G, and C strings, averaged over all samples.
- createStringSetTable() creates a table for one string set, plotting intensities of harmonics against sample notes. The table title is the string brand, rows are harmonic numbers, and columns are sample notes (open A, B on G string, etc.).
- createSampleTable() creates a table for one sample note, plotting intensities of harmonics against string brands. The table title is the sample note, rows are harmonic numbers, and columns are string brands.
- createStringTable() is similar to createSampleTable, but averages the results of

all notes on a given string. The table title is the string name, rows are harmonic numbers, and columns are string brands.

Once the program was executed, the output was read into OpenOffice.org Calc, a free spreadsheet program similar to Microsoft Excel, to generate graphs for this study.

Chapter 5. Analysis

5.1. Interpreting the Data

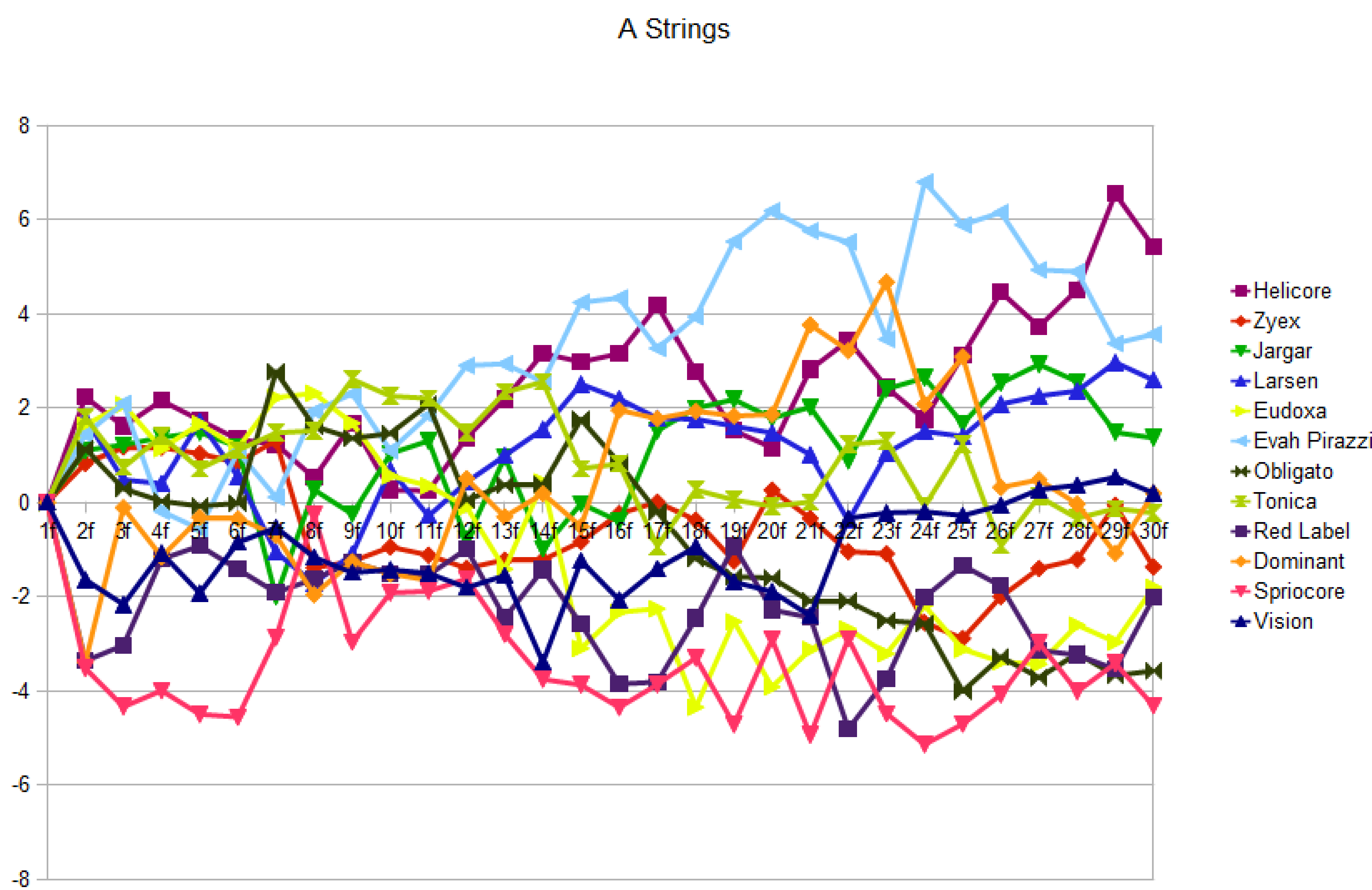
The graphs presented all plot harmonics against relative intensity. That is, the notches 1*f*, 2*f*, etc. on the horizontal axis are multiples of a fundamental frequency *f*. The vertical axis in each graph shows decibels, and points plotted show the difference between a sample (or average of samples) and a baseline average. Curves represent harmonic spectrum envelopes. Each curve originates at (1*f*, 0), because we subtracted the fundamental intensity from each measurement, effectively normalizing the curves by fundamental strength—reducing the effect of small differences in volume between samples and making it easier to see the shape of each curve. Time is not represented in the graphs, because with LTAS the time dimension is averaged out.

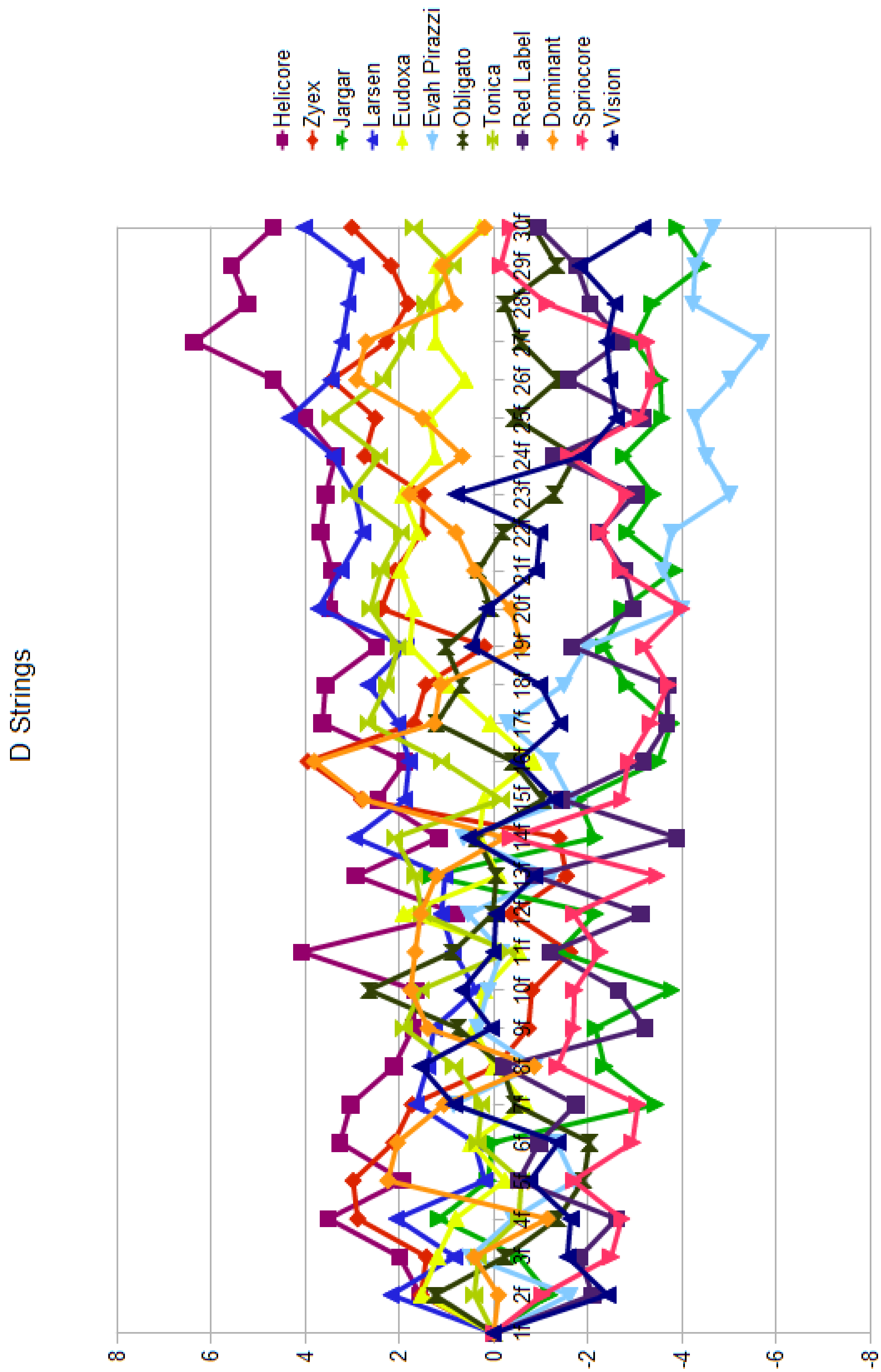
String timbre, compared to other instruments, tends to have a range of harmonics, balanced between low, middle, and higher harmonics (Campbell and Greated 1987, 151). Deviations from average can produce different effects. One of the most noticable effects is brightness or sharpness, caused by strength in high harmonics. Relatively weak higher harmonics can produce dullness. Since the graphs have been normalized by fundamental strength, a curve that is mostly above zero shows a spectrum where higher harmonics dominate the fundamental—a brighter sound—where a curve that lies below zero shows a fundamental-heavy, duller sound.

Another consideration is the *blend* of a string set. By "blend" we mean the similarity of timbre among the A, D, G, and C strings in a set. (This is different from *consistency of manufacture*, which is not addressed in this study.) The graphs presented here show each string in a set separately. One might expect that purchasing four strings in a "set" would guarantee well-matched timbres among the strings, but in fact some brands are matched more closely than others. Some musicians will prefer blended string sets, while others may like the range of colors possible when using a more diverse set. Different degrees of blending may be suitable for different purposes (e.g., chamber or orchestral vs. solo performance). The string set graphs produced here can be used to compare the range of colors within a set against the alternatives, as discussed in section 5.3.

5.2. Graphs

We present here four graphs comparing each string in the twelve sets studied. Then we look at each string set separately, showing open string results in twelve more tables. The scales have been matched for easy comparison.


A Strings
8
6
4
2
0
-2
-4
-6
-8
1f 2f 3f 4f 5f 6f 7f 8f 9f 10f 11f 12f 13f 14f 15f 16f 17f 18f 19f 20f 21f 22f 23f 24f 25f 26f 27f 28f 29f 30f
Helicore
Zyex
Jargar
Larsen
Eudoxa
Evah Pirazzi
Obligato
Tonica
Red Label
Dominant
Spriocore
Vision


D Strings
Helicore
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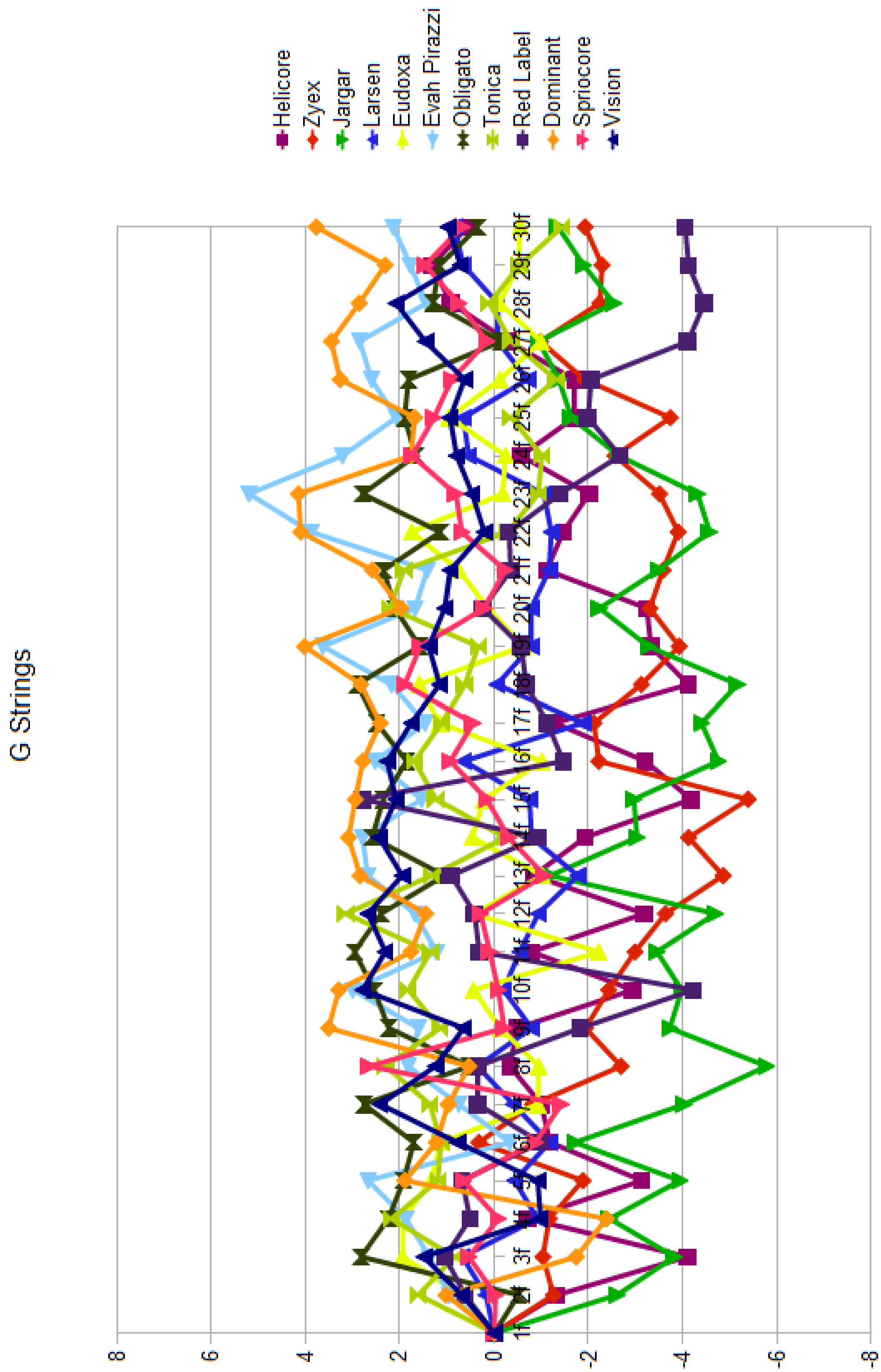
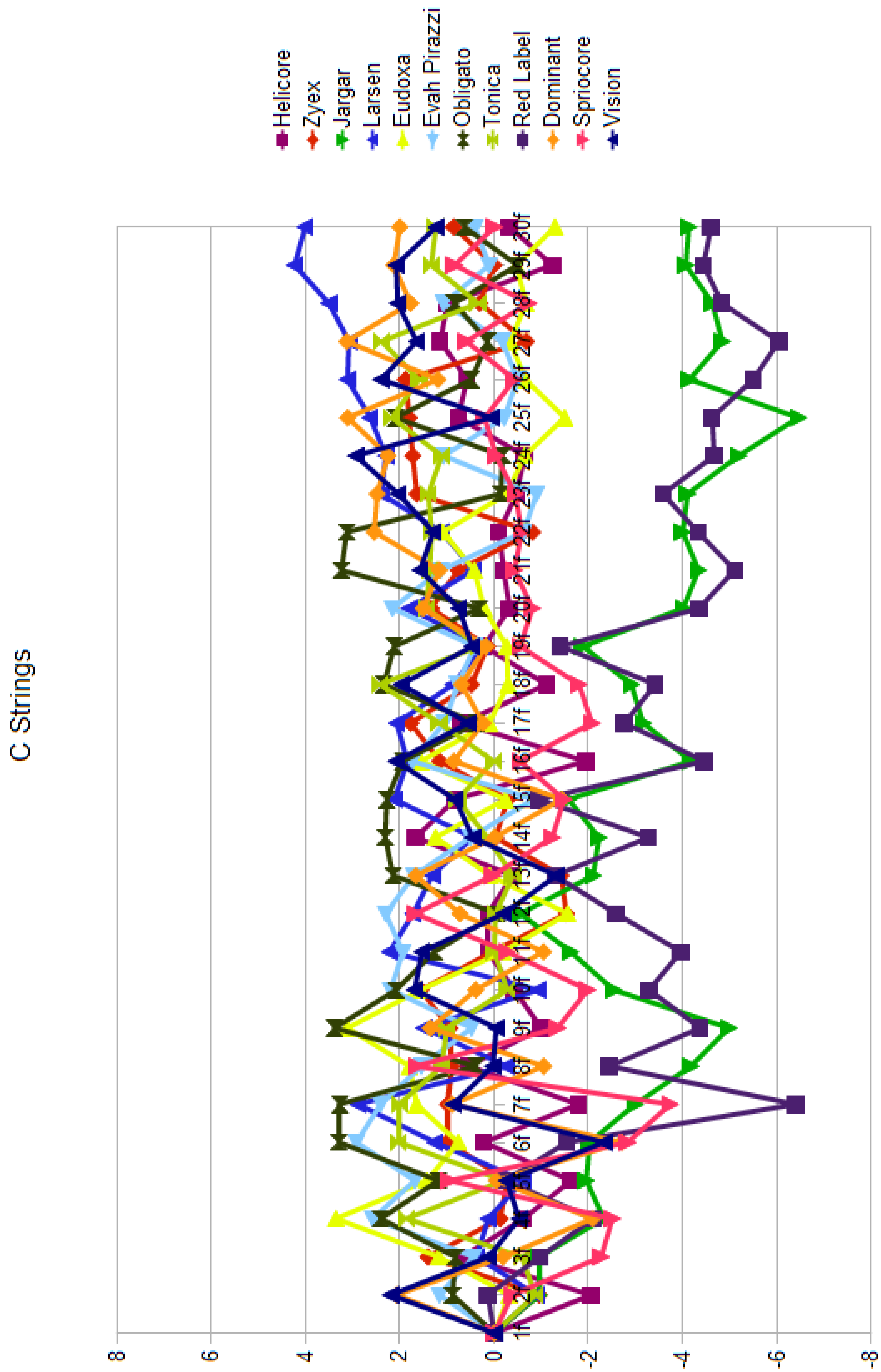
Eudoxa
Evah Pirazzi
Obligato
Tonica
Red Label
Dominant
Spriocore
Vision


G Strings
Helicore
Zyex
Jargar
Larsen
Eudoxa
Evah Pirazzi
Obligato
Tonica
Red Label
Dominant
Spriocore
Vision


C Strings
Helicore
Zyex
Jargar
Larsen
Eudoxa
Evah Pirazzi
Obligato
Tonica
Red Label
Dominant
Spriocore
Vision
8
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2
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-6
-8
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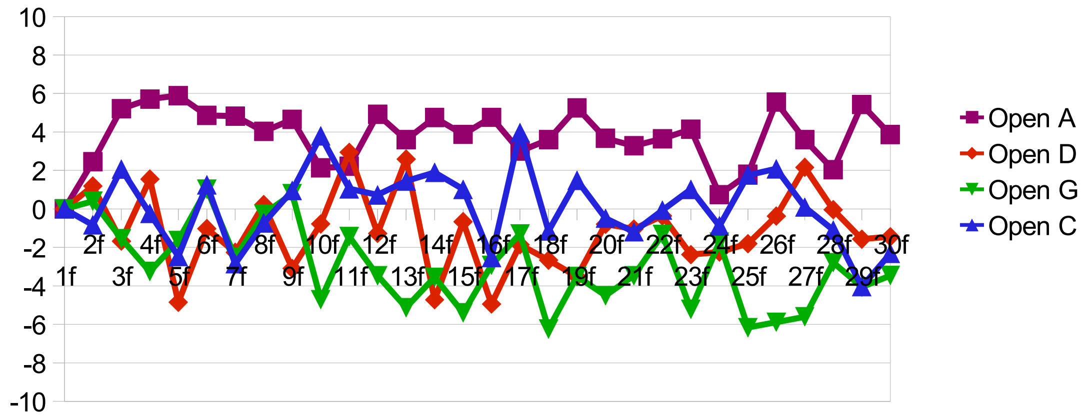
1. Helicore



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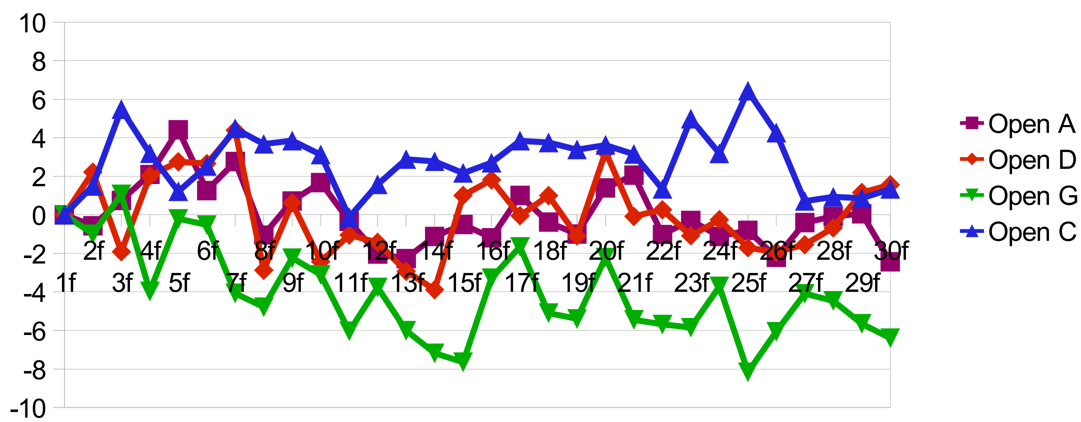

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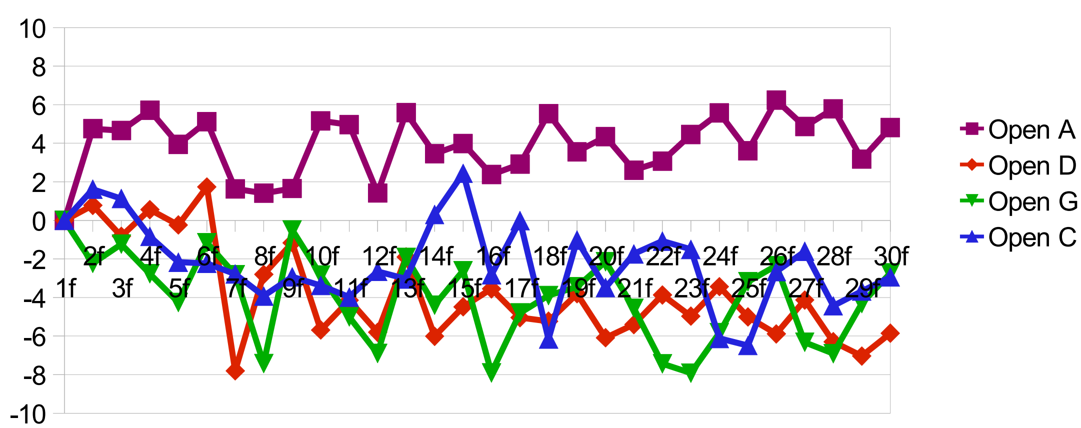

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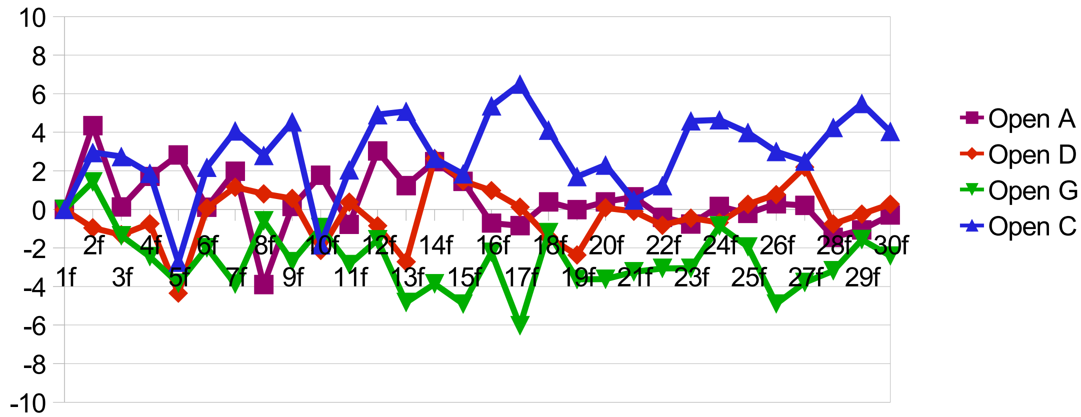

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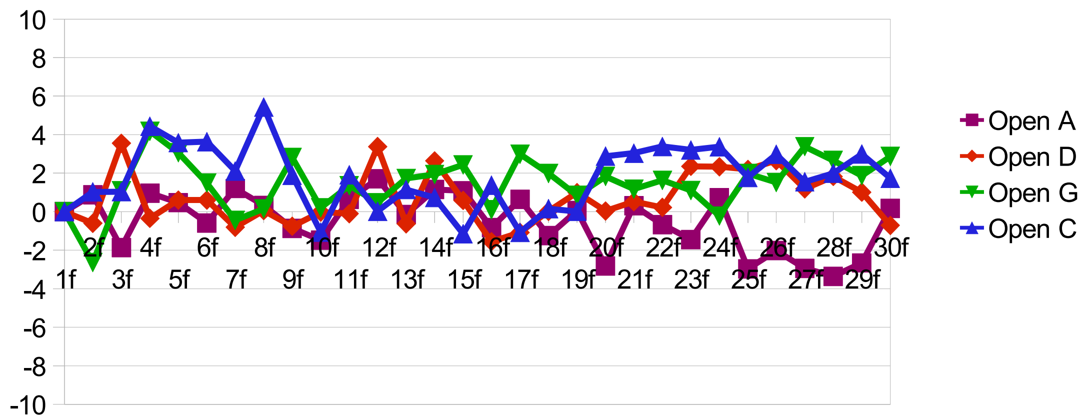
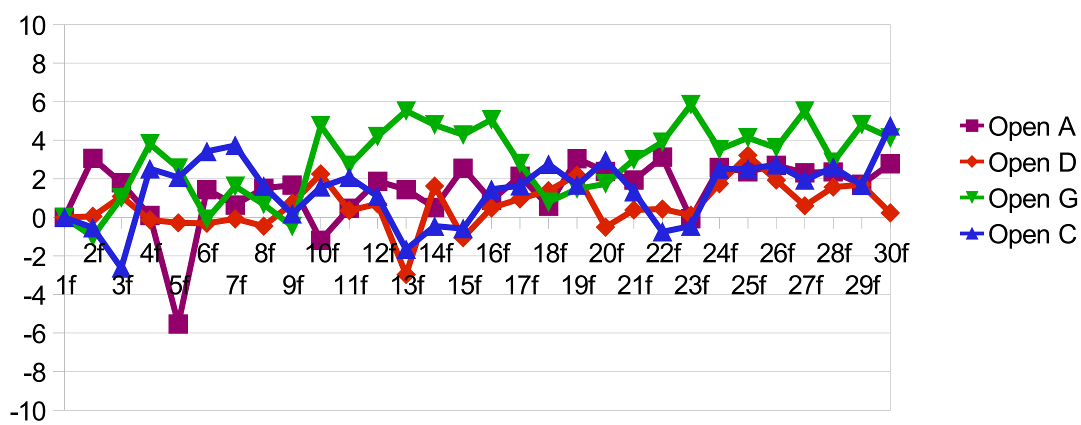
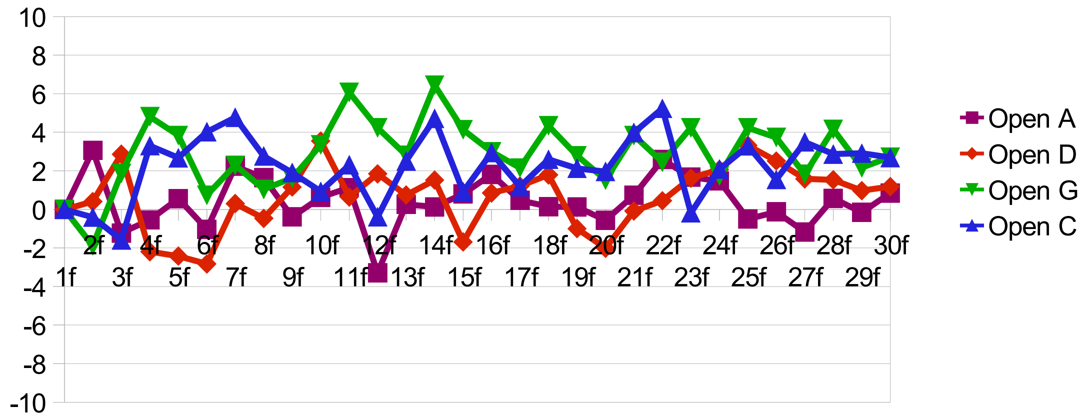


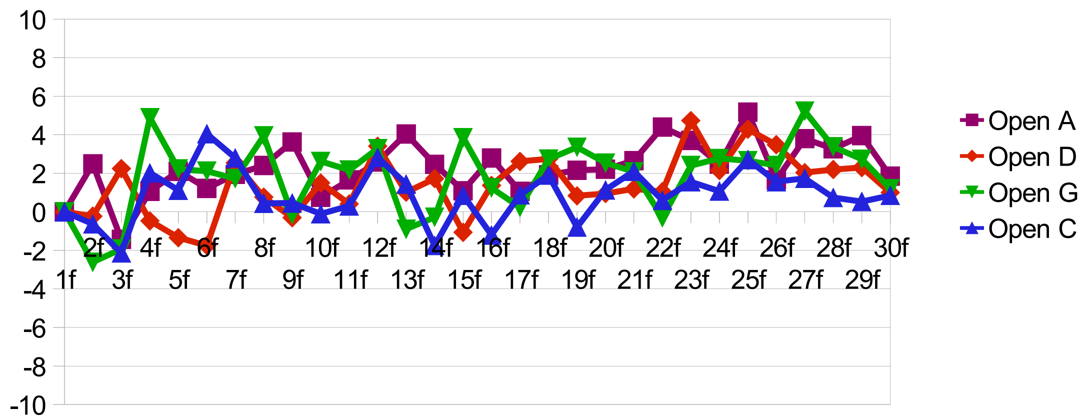
6. Evah Pirazzi



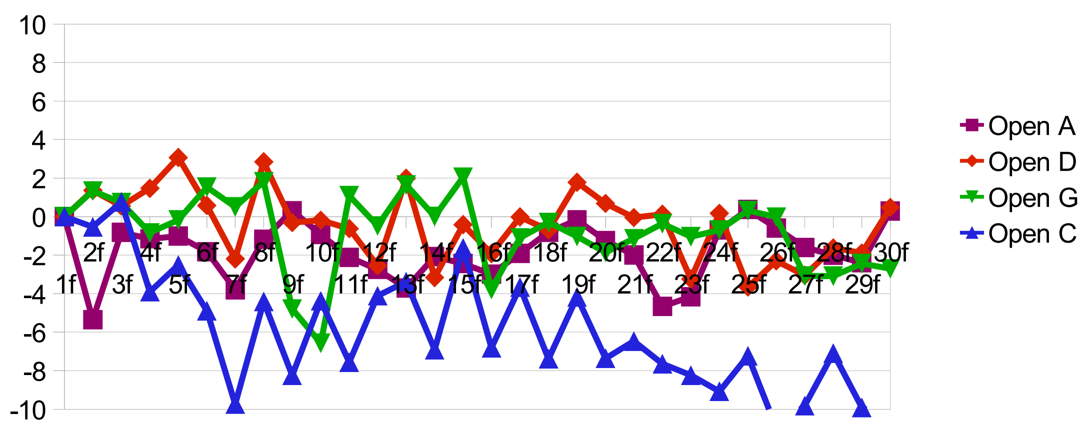
7. Obligato



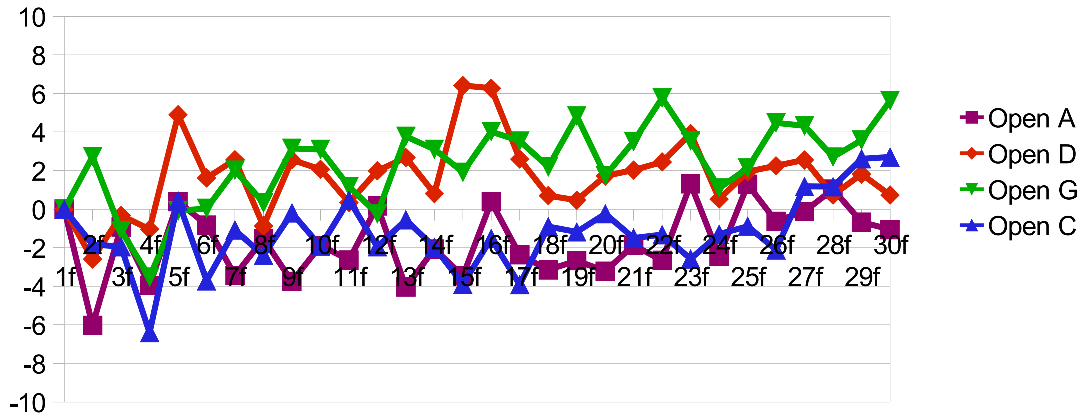
8. Tonica



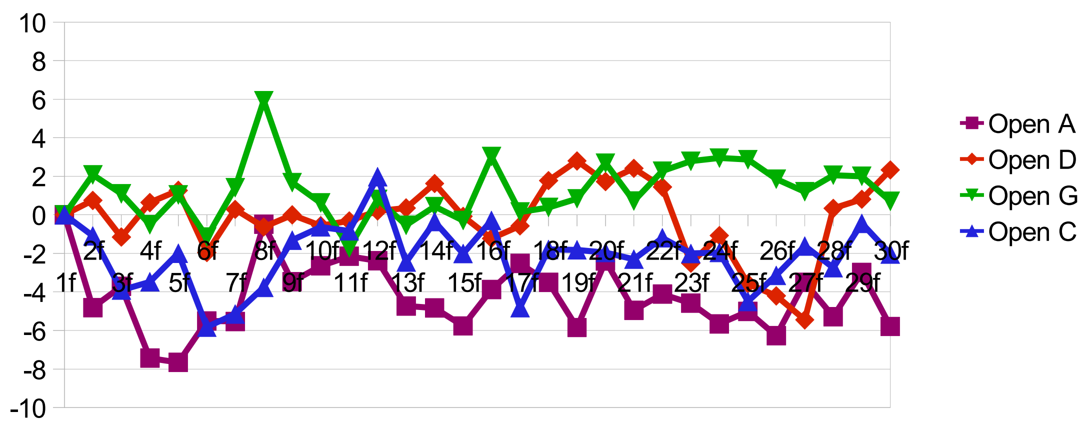
9. Red Label



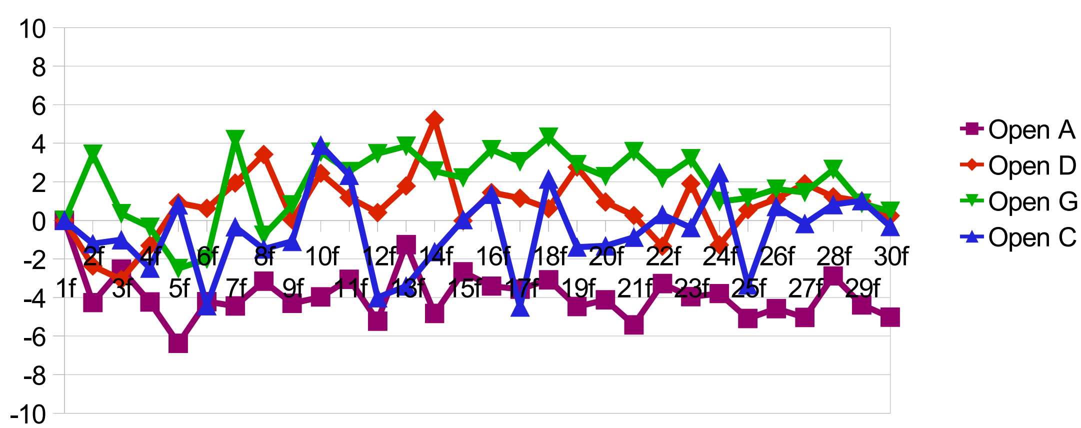
10. Dominant



11. Spirocore



12. Vision



5.3. Comments

The "most average" string type in the group of strings used for this study is the Eudoxa gut string set. In the Eudoxa open string graph, and in the four string comparison graphs, the curves for all four Eudoxa strings tend to hover around zero, showing minimal differences from the overall average spectra. To the extent that the twelve sets of strings we used represent the range of expected tone colors for the viola, the Eudoxa strings appear to sit right in the middle. While we did not attempt to statistically sample string brands, we did attempt to choose a variety of types and compositions, as mentioned in section 4.1. In any case, the Eudoxa set makes a good benchmark for subjective aural comparisons.

We briefly comment on the spectral data for each string set. These notes are based on the charts above and were confirmed by listening to recorded samples, including individual notes and Bach recordings. The comments use a small number of descriptive words, mostly comparing brightness (emphasis in high harmonics, visible as curves that move upward from the fundamental) among the sets and within each set. The danger with this approach is oversimplification, but the advantage is clarity and consistency. Here we deliberately avoid value-laden words like "shrill" (too bright) or "dull" (too dark).

1. D'Addario Helicore—offers bright A and D strings, with a darker G.
2. D'Addario Zyex—a fairly average set, except for a dark G and a slightly brighter C.
3. Jargar—very bright A and dark D, G, and C. Makes for a striking effect when crossing between D and A.

4. Larsen—overall a bright set.
5. Pirastro Eudoxa (gut core)—average all around, useful as a benchmark for subjective comparisons.
6. Pirastro Evah Pirazzi—bright A and G, with less bright D and C. The A is very strong in upper partials, as we see in the "A Strings" table.
7. Pirastro Obligato—average A and D, brighter G and C.
8. Pirastro Tonica—a little brighter than average, but not as much as Larsen.
9. Super Sensitive Red Label—dark, especially the C. The Red Label C is the most extreme example of all the strings, showing a large deviation in spectrum shape from average, though the Jargar C is close. The Red Label C heavily weighted towards the fundamental and lower harmonics compared to other C strings.
10. Thomastik Dominant—D and G are brighter than average, with darker A and C, so the middle strings are aurally emphasized.
11. Thomastik Spirocore—dark, with D and G less so.
12. Thomastik Vision—dark A, brighter D and G. Interestingly, all three of the string sets from Thomastik tend toward increased brightness in the middle strings.

One result worth noticing is that the composition of a string is not an entirely reliable predictor of the string timbre. For example, steel strings are stereotypically supposed to be brighter, but in fact some of the darkest strings were steel—the lower Jargar strings, Red Label C, and Spirocore. Larsen, one of the brighter sets, uses a synthetic core except for its steel A. Some of the steel strings were actually bright, like the Helicore upper strings and the Evah Pirazzi A string.

There is no "correct" timbre; the violist must choose a string that suits his or her preferences and works well on the available instrument. Since different instruments have different response curves, a violist should consider the sound of his or her instrument when selecting strings. A viola with weaker response in certain ranges can be complemented by an appropriate set of strings; one with a brilliant response might be well-suited to warmer strings. One should also consider the primary intended use of the strings. A soloist might prefer brighter strings to help clarity and projection above the piano or orchestral accompaniment. Someone who frequently performs older music or is interested in historical performance practice may prefer gut for a more authentic sound—but if gut strings prove too unwieldy, the musician might try others that have a similar sound.

5.4. Other Considerations

During this study, none of the strings broke, and none appeared to be false or defective. Consistency of manufacture is a consideration beyond the scope of our work, but there were no obvious flaws in the materials used.

Several inaudible considerations are also worth mentioning. Some of these factors are difficult to define scientifically, but for completeness we describe subjective impressions made on this author during the course of this research. "Playability," meaning the response of the string to the bow action, varies greatly with string material. The Eudoxa gut strings "felt" the best under the bow hand, responding quickly and without resistance. The Red Label strings were the most difficult to play. In addition, the Red Label strings exhibited the most pitch bending as a result of bow pressure, making intonation difficult to control. As discussed in chapter 2, these effects can be symptoms of string stiffness. Other strings with particularly good response were Zyex, Dominant, and Vision; the Obligato strings were less responsive and more susceptible to pitch bending. Mixing strings from different sets sometimes interfered with playability, as the required bow force changed with each string crossing.

Ease of tuning and tuning stability may also be important to the musician. The only string set that had serious stability issues was the Eudoxa gut set, which almost never managed to stay in tune over night. This is a well-known property of gut strings, as mentioned in chapter 3. Some strings tune up and down more rapidly with respect to peg adjustment distance. The easiest strings to tune were the ones that required larger peg movements to achieve a given pitch shift; when a small peg adjustment greatly affects the pitch of the string, tuning is difficult without fine tuners. Measuring this effect was beyond the scope of this study, but it is probably related to the tension and density of the string, as these components are non-linearly proportional to pitch (see chapter 2).

5.5. Conclusion

This research compared 12 sets of viola strings, focusing on timbre as measured by spectrograms. Our work should help the violist who is interested in achieving a different sound but cannot afford to purchase many different kinds of strings. The data and analysis will guide the musician as he or she forms a frame of reference for judging strings, and the note samples and Bach recordings will let him or her make a personal artistic decision. We welcome future efforts to compare and evaluate viola strings, including more brands, different kinds of samples, more violas, and more subjective reviews from professional musicians.

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Appendix A. Multimedia Index

1. Recordings of individual notes (WAV files, 576 files, 408 MB total)

   File name format is "1_2_3_4.wav":

   1. String set (see section 4.1)
   2. Instrument (see section 4.1)
   3. String (1 = A, 2 = D, 3 = G, 4 = C)
   4. Sample note (1 = open string, 2 = major third above open string, 3 = perfect fifth above open string)

2. Recordings of Prelude from *Suite No. 1* by J.S. Bach (WAV, 24 files, 340 MB total)

   File name format is "bach_1_2.wav":

   1. String set (see section 4.1)
   2. Instrument (see section 4.1)

3. AutoHotKey script to extract spectrogram data from all audio samples (AHK, 1.53 kB)
4. Java source code for aggregating harmonic spectrum data (JAVA, 4 files, 16.7 kB total)
5. Spreadsheet with raw output of Java program (CSV, 190 kB)