The Effect of Wood on Electric Guitar Timbre

An Honors Thesis

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Submitted to the Texas A&M University-Commerce Honors Committee in partial fulfillment of the Program of Honors Study leading to the degree of Bachelor of Computer Science.

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PREFACE

This thesis is submitted to the Texas A&M University-Commerce Honors Committee in partial fulfillment of the Program of Honors Study leading to the degree of Bachelor of Computer Science. However, one will not find much related to computer science in this study, as it focuses on the acoustic properties of wood and its effect on the timbre of the electric guitar. As a guitarist, home music producer, and programmer, I found myself wanting to blend multiple interests together for my thesis study. After seeing many endless heated discussions online about how much of a difference wood type makes on the sound of an electric guitar I realized that the discussion is mostly subjective with little scientific evidence. I decided I wanted to shed some more light on the subject and was able to create an experiment free of subjective ideas of what good or bad timbre is.

I created two identical guitars and compared their timbre for differences, conducting the experiment entirely by myself in the convenient location of my dorm room. Data collection was a lengthy process with many setbacks including broken strings, drifting pitches, and inconsistent data. After these setbacks I reevaluated my old methodology and came up with a new one, used in this thesis, that was able to produce consistent results. The results, unlike the online debates, are not extreme, but they provide meaningful statements as well as a stepping stone into more research.

Acknowledgements

First and foremost, I would like to extend my sincerest gratitude to my thesis advisor Dr. Carlos Bertulani, who, despite his busy schedule and extensive travels, consistently made the time to assist and guide me through this process. His oversight and help were invaluable in allowing me to conduct an experiment outside of my field of study. I would also like to thank Dr. Green, the Dean of the Honors College, whose door was always open. His input was much appreciated when reevaluating my methodology despite closing deadlines. Thank you also to my honors advisor Dr. Villanueva-Russell and to Dr. Sirakov for taking part in my thesis proposal as well as my defense. Further thanks to my guitar professor Tim Goynes, whose advice was very helpful in deciding how to construct the guitar. I am also extremely thankful for all of Bill McGuffin's help. Through his generosity and skillful carpentry I was able to conduct my research in a legitimate manner and with all of my fingers. I am very appreciative of my fiancée's support and all the help she gave with revising and editing. Lastly, I would like to thank my parents and my Grandma Eleanor for instilling in me a passion for music.

ABSTRACT

The importance of the quality of wood used in an acoustic guitar is seemingly intuitive, as the resonance of the wood is necessary to generate an audible sound from the instrument. The innovation of the electric guitar that allows an electric current to be generated as result of magnetic induction in a pickup rendered the old style of guitar construction unnecessary for electric guitars. This study aims to quantify the difference the type of wood used in an electric guitar makes on the tone quality, or timbre, of the sound produced by playing the guitar.

Timbre is defined in this study as the ratio of the amplitude of the harmonics of a note relative to its fundamental pitch. Two guitars were constructed identically with the only difference being the types of wood used, specifically maple and mahogany. Three different strings were placed on the guitars; each was plucked to produce notes that were analyzed for differences in timbre across the woods.

The maple had more harmonic content than the mahogany for the low E string, while the opposite was true for the D string. The timbre of the high E string was similar for both woods, as the maple had more amplitude for the even harmonics except the 10th, while the mahogany had more amplitude for the odd harmonics. Overall the differences in the harmonics for the high E string present in each wood evened each other out.

The difference in timbres for each wood depends on the string being analyzed. On average there is not a brighter or warmer wood; each one is simply different, and it varies from string to string.

INTRODUCTION

The principal difference between the electric guitar and its acoustic ancestor is the mechanism used to amplify the sound produced by plucking the strings. Acoustic guitars rely on the ability of the wood to vibrate with the strings, allowing the sound waves to resonate in the body and propagate away from the guitar (Hall 1980; Olson 1967). Consequently, the acoustic properties of the wood used will have a certain impact on the sound quality, or timbre, of the tone produced (Sedik 2010). However, the electric guitar relies on the ferrous strings to induce a current in the magnetic pickups placed under the strings (Wheeler 1978), which is then sent to an amplifier to be played through a speaker.

The wood does not need to resonate for the string to induce a current in the pickup, but the idea that wood type directly affects sound quality has been applied to the electric guitar in publications and media (Sweetwater 2013; Wormoth Custom Guitars & Bass Parts). Even so, a study in 2012 showed that humans could not distinguish between an acoustic guitar made of wood and one made of polymer when given blind sound tests (Pedgley and Norman 2012). If the quality of the construction of an acoustic instrument is difficult to perceive audibly, then the importance of the wood in an electric guitar must also be evaluated.

The amount of peer-reviewed research on this subject currently is lacking; an article published by a university in Australia claims that a researcher has proven that wood does not affect a guitar's sound, but no data has been published together with this assertion. (La Trobe University 2012). Keith J. Soper from the University of Toledo conducted a study that compared the difference in timbre between a guitar with a body made from ash and another from alder. Butch Lafelice of Calaveras Fretworks Custom Guitars also conducted the same experiment comparing a guitar with a body made of ash and another from mahogany. Both studies showed a slight difference in timbre, but each guitar was not entirely made from one wood; rather, the same neck was used and transferred across guitars. Another possible issue in these two studies was the lack of control over the velocity at which the strings were plucked, as they were plucked by hand each time.

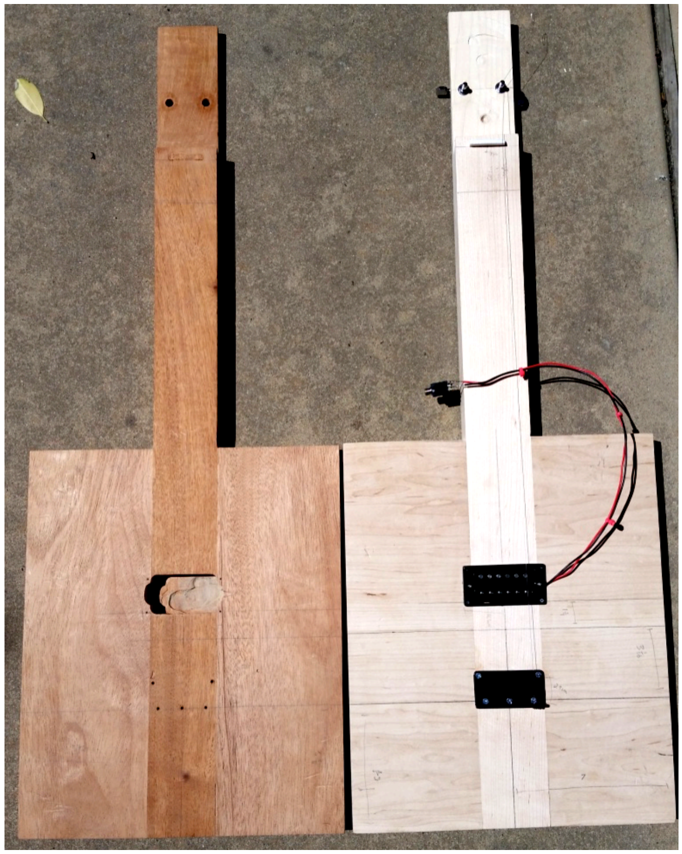
Merriam Webster defines timbre as "the quality given to a sound by its overtones". For the purposes of measuring timbre in a way that is comparable regardless of differences in amplitude of two notes, timbre will be defined as the ratio of the amplitude of harmonic overtones to the amplitude of the fundamental pitch. A timbre that is "bright" would have overall higher amplitudes for its harmonics above the fundamental, whereas a warm timbre would have less. Using these definitions, this study aims to quantify the effect the type of wood makes on the timbre of sound produced by magnetic pickups of an electric guitar, making sure to eliminate differences in picking velocity and construction materials.

MATERIALS AND CONSTRUCTION

Construction of the Wood

Two simple guitars were constructed out of maple and mahogany, with only one wood used per guitar. These woods were chosen for their dissimilarity; maple is said to have a brighter tone with more harmonics, while mahogany is said to have a warmer tone with less harmonics (Sweetwater 2013; Wormoth Custom Guitar & Bass Parts). The overall shape of the guitar was very simple, with a rectangular body and neck glued together as one continuous piece of wood. No frets or fretboards were used for the sake of simplicity.

Picture 1 Guitars. Mahogany on left with no hardware, maple on right with all hardware.



The measurements for each guitar in centimeters are listed below. The volume of each section is added together, and the volume for the pickup route is subtracted. The pickup route is not completely square, so this is a very close approximation. There is no difference in measurements greater than 3 mm.

Table 1 Maple Dimensions

Section	Length (cm)	Width (cm)	Height (cm)	Volume (cm^3)
Body	43.3	35.7	3.5	5410.3
Neck	37.0	7.5	3.5	971.3
Headstock	16.3	7.5	1.3	158.9
Pickup Route	4.0	8.5	2.5	85.0
			Total:	**6455.5**

Table 2 Mahogany Dimensions

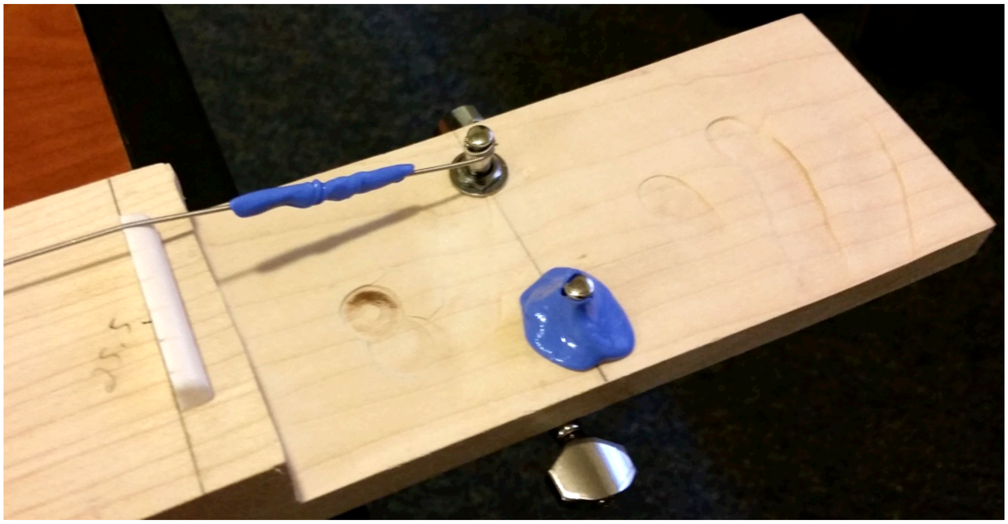
Section	Length (cm)	Width (cm)	Height (cm)	Volume (cm^3)
Body	43.3	36.0	3.5	5455.8
Neck	36.9	7.5	3.5	968.6
Headstock	16.5	7.5	1.5	185.6
Pickup Route	4.0	0.5	2.5	5.0
			Total:	**6605.1**

The weight for the maple guitar without hardware was 4.1 kg, and the weight for the mahogany guitar without hardware was 3.5 kg. These measurements indicate that the maple had a density of 0.64 g/cm^3, and the mahogany had a density of 0.53 g/cm^3.

Guitar Hardware

Each guitar consisted only of a bridge, a humbucker pickup, a nut, and 2 tuning pegs. The humbucker was wired directly to an output jack without the volume or tone knobs that are typically present on a guitar. The guitars used a top-mount hardtail bridge from GuitarFetish.com, a Gibson-style nut from GuitarFetish.com, brandless Fender-style chrome tuners, an Ibanez humbucker, and a female TRS jack wired as a TS jack. To ensure that the only difference between the two guitars was the wood, the same individual components were used for both, requiring that each component be removed from the guitar when done testing so it could be placed onto the other.

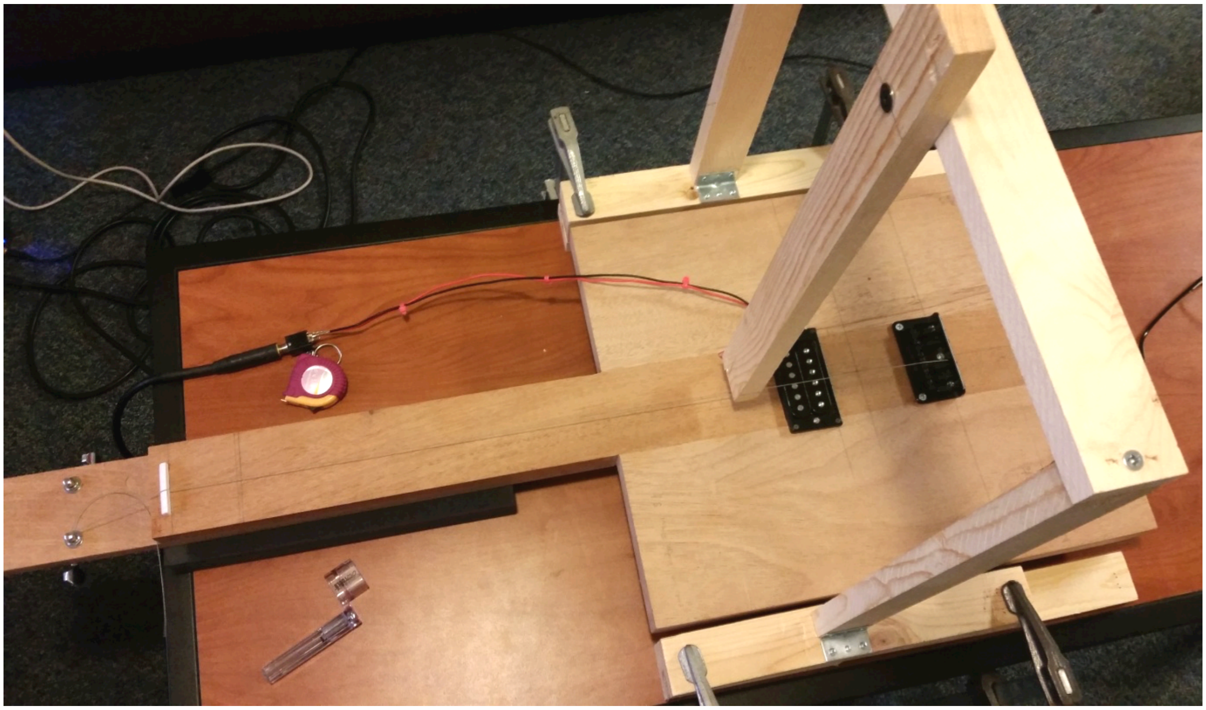
Picture 2 Tuning pegs and nut on the head of the guitar. Note the putty used to reduce vibration of the string behind the nut, as well as the other tuning peg.



Apparatus to Pluck the Strings

An apparatus was created to pluck the strings of the guitar at the same location on the string and the same velocity every time. This consisted of a square frame that allowed for a guitar plectrum affixed to the end of a strip of wood to swing in one direction as a pendulum, reliably striking the string when swung from the same height. The supports on the bottom of the square frame were secured to a table via wood clamps to prevent movement.

Picture 3 Picking apparatus over the guitar, secured to the table with clamps. The guitar is on sound isolation pads.



Sound Isolation

Each guitar was placed onto a table underneath the frame of the plucking apparatus, with Auralex Acoustics MoPAD Monitor Acoustic Isolation Pads underneath the guitar. The guitar was positioned between the sides of the frame of the plucking apparatus exactly 8mm from the side of the guitar closest to the low E string. This isolation from the table and the plucking apparatus minimized the amount of vibration that could be transferred from the guitar into the table or plucking apparatus and vice versa.

Recording Hardware and Software

The humbucker was connected to an M-Audio Fast Track 2 USB interface via a 12 ft TS cable with the input gain set at 12 o'clock. The samples were recorded with Presonus Studio One v2.6 at a bit depth of 16 bits, a sample rate of 44.1 kHz, in mono format.

Picture 4 Screenshot of Presonus Studio One 2.6 recording the data.

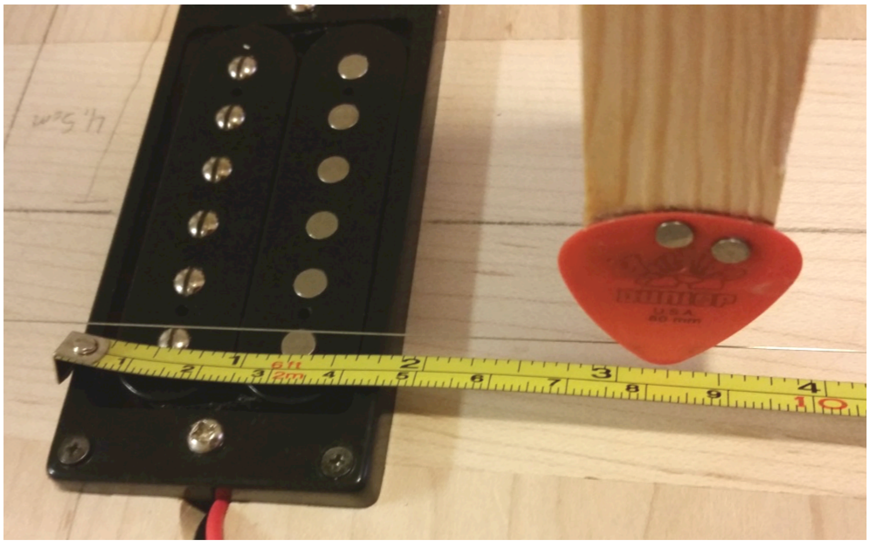
Guitar Strings

Three strings were used for the experiment: a high E, a D, and a low E. The E strings are the highest and lowest found on a regular electric guitar in standard tuning. The D string was chosen because its pitch is very close to being halfway between the other two strings . A D'addario EXL115 .052 gauge string was used for the low E, an Elixir Nanoweb .010 gauge string was used for the high E, and an Elixir Nanoweb .026 gauge string used for the D string. Different brands were used due to a string breaking during testing that required the closest available string to be used. Old strings were used for their tonal consistency as an effort to avoid the tonal inconsistencies of new strings. The low E string was previously on a guitar for approximately nine months and the high E and D strings were on another guitar for approximately six, both having been played around two hours a week.

Methodology

For each string 40 samples were collected by raising the pendulum of the plucking apparatus to the same height each time and letting go, plucking that string at the same spot every time, 8.3 cm from the bottom of the pickup as demonstrated in Picture 5. The pendulum was then secured by hand, preventing it from falling back drown and striking the string prematurely. The pendulum would then be brought back around and let go to strike the string again after 45 seconds, resulting in a 30-minute audio recording containing 40 notes each 45 seconds apart.

Picture 5 Measuring the location on the string that the pick will hit.



Data Processing

Each audio file was normalized by bringing the loudest peak up to -0 decibels relative to full scale (dBFS) and then exported as a .wav file at a bit depth of 16 bits, a sample rate of 44.1 kHz, and in mono format. Each audio file was then analyzed by Harmometer by Vobarian Software. The default settings were used with the exception of two parameters: the attack length was set to 0 seconds and the FFT size set to 16,384 samples. These two changes respectively allowed the attack to be analyzed for harmonic content along with the rest of the note, and set more samples to be used for better pitch detection.

Measuring Amplitude

Harmometer uses a simplified discrete Fourier transform to measure the amplitude of the 1^{st} to 11^{th} harmonics of a detected fundamental frequency (Bercheck 2009), where the 1^{st} harmonic is the fundamental frequency and each successive harmonic is the n^{th} multiple of the fundamental frequency. The amplitude was measured directly from the input .wav file, where it is stored as a value from -2^{15} to $2^{15} - 1$, a range consistent with the 16 bits available to represent this. This range allows for representation of decibel levels from -96 dBFS to 0 dBFS, where 0 dBFS is the highest amplitude that could possibly be encoded in the digital signal. An increase in 6 dB corresponds with a doubling of the amplitude encoded in the .wav file.

Transforming Data for Better Comparability

The text output was imported into Microsoft Excel where the measured amplitude of each harmonic for a note was divided by the amplitude of the fundamental frequency. This transformed the data to represent the presence of each harmonic as a ratio relative to the fundamental, creating a measure that allows for the timbre of two trials to be compared by accounting for differences in overall volume. The relative amplitude of the n^{th} harmonic rA_n can be defined as

$$rA_n = \frac{A_n}{A_1}$$

where

$$n = harmonic\ number$$
$$A = amplitude\ of\ a\ given\ harmonic$$

RESULTS

Table 3 shows the mean relative amplitude for harmonics 1 through 11, where harmonic 1 is the fundamental frequency and each successive harmonic is the next integer multiple of the fundamental, e.g. for a fundamental frequency of 100 Hz, the 1st harmonic would be 100 Hz and the 11th harmonic would be 1100 Hz. 40 samples were taken per string per guitar and their relative amplitudes were averaged together to generate the final averages presented in the following tables.

Table 3 Mean Relative Amplitudes

		Harmonic Number										
Wood	**String**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Maple	Low E	1	2.5709	1.1714	0.4516	0.296	0.0605	0.08548	0.0423	0.0472	0.00824	0.0047
Mahogany	Low E	1	1.4602	1.1138	0.2259	0.3018	0.0359	0.1382	0.06565	0.1767	0.09481	0.0215
Maple	D	1	0.78611	0.47981	0.1781	0.1947	0.0270	0.06323	0.06756	0.1933	0.07058	0.0172
Mahogany	D	1	1.3032	0.90909	0.09051	0.21076	0.0227	0.1187	0.05780	0.1775	0.08089	0.0150
Maple	High E	1	1.5161	1.1336	0.74175	0.6078	0.1252	0.2904	0.2467	0.70811	0.3100	0.0248
Mahogany	High E	1	1.0283	1.2216	0.60464	0.83384	0.0626	0.3505	0.1127	0.94860	0.62972	0.08714

Figure 1 provides a visual representation of the difference between the timbre of the low E on the different guitars. The maple guitar has a noticeably higher amplitude for the 2nd harmonic, as well as higher amplitude for the 4th. The mahogany has a higher amplitude at the 9th harmonic, but the differences in the 5th through 11th harmonics are small.

Figure 1 Low E Mean Relative Amplitude

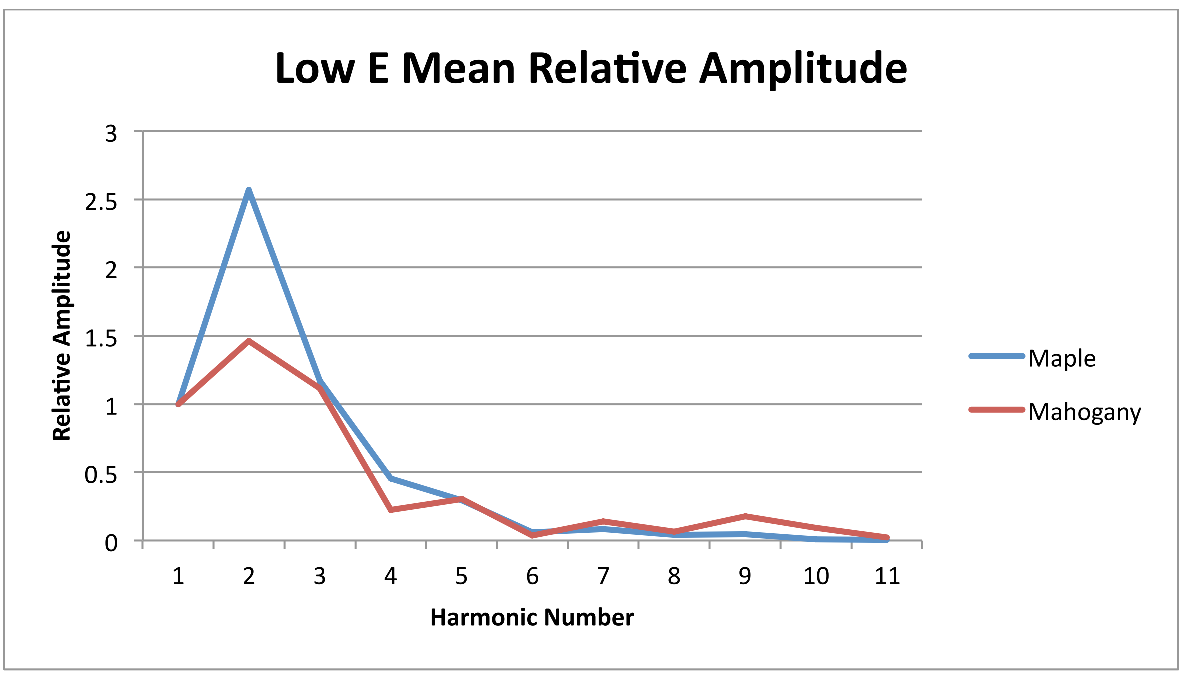


Figure 2 shows that the mahogany guitar has noticeably more amplitude for the 2nd and 3rd harmonics on the D string, with only small differences in the others.

Figure 2 D Mean Relative Amplitude

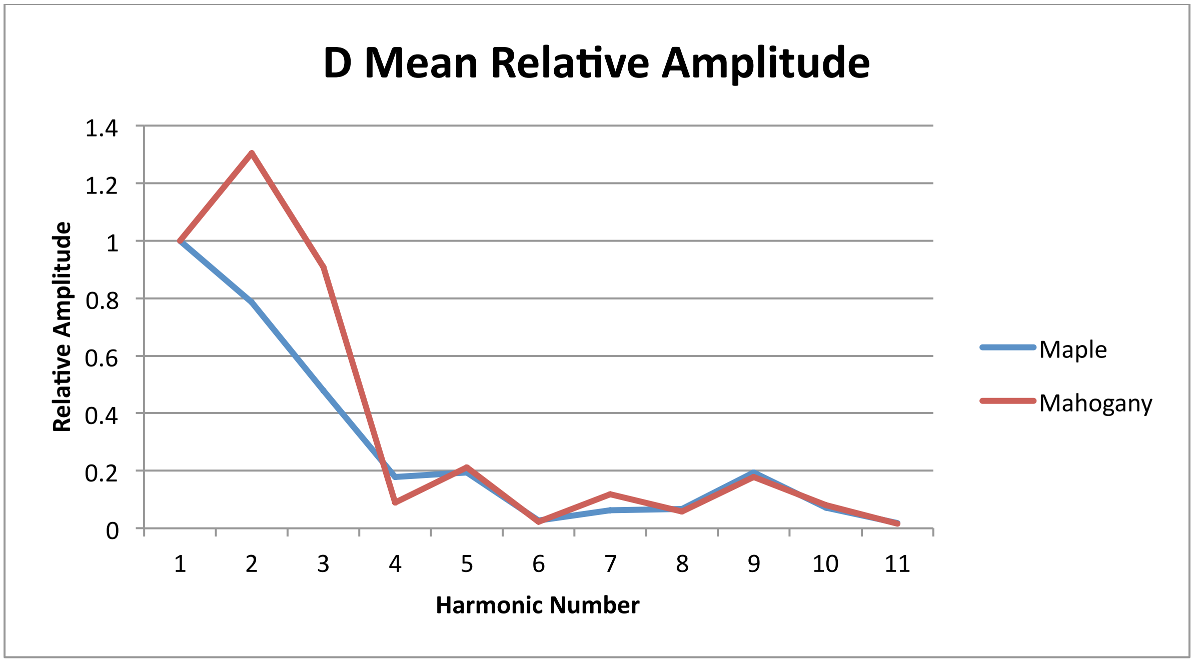


Figure 3 shows that the maple has more amplitude for the even harmonics except the 10th for the high E string, while the mahogany has more amplitude for the odd harmonics.

Figure 3 High E Mean Relative Amplitude

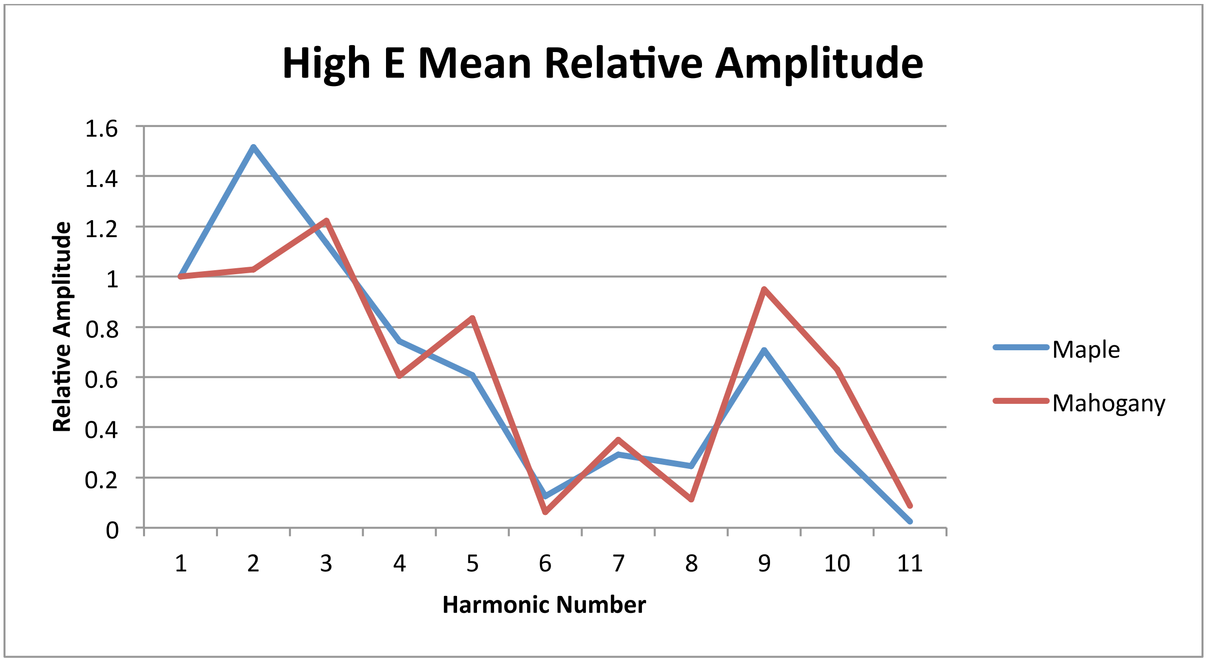


Table 4Table 4 is particularly useful when comparing overall timbre for each wood. The ratio of the mean relative amplitude of a harmonic on the maple guitar to the mahogany guitar gives us an indicator of how many times greater or lesser the amplitude is for the maple over the mahogany. A shaded cell indicates that the maple has greater amplitude for the specified frequency, and a non-shaded cell indicates that the mahogany has a greater amplitude. Yellow indicates that the average for each wood is equal. The average column indicates that on average, the maple has higher amplitude harmonics than the mahogany for the high E, while the mahogany has higher amplitude harmonics for the low E. The difference, however, is very small. The average for the D string is 0, meaning that on average one wood does not have louder harmonics.

Table 4 Ratio of Maple to Mahogany Mean Relative Amplitudes

	Harmonic Number										
String	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Average**
Low E	1.7606	1.0517	1.999	0.982	1.69	0.6188	0.644	0.267	0.0869	0.22	0.93
D	0.60320	0.5278	1.968	0.9240	1.19	0.5328	1.169	1.089	0.8726	1.151	1.00
High E	1.4744	0.92794	1.2268	0.7289	2.00	0.8286	2.190	0.74648	0.4923	0.285	1.09
										Average:	**1.01**

This would indicate that while the timbres for the two woods are different, one is not specifically brighter than the other. However, the graph for the D string in Figure 2 does not look like the two timbres balance each other out. The harmonics that stand out visually are those closest in relative amplitude to the fundamental harmonic. These harmonics, specifically harmonics 2 and 3, have more amplitude on the mahogany guitar, and no other harmonics on the maple guitar are as high in relative amplitude for the D string. The same is true for the low E string graph in Figure 1; it would indicate that the maple has more harmonics, yet the previous table says exactly the opposite. Therefore, it would be more valuable to compare harmonics that are loudest, as they affect the sound the most.

Table 55 below is a copy of the previous table of ratios containing only the data for the loudest harmonics. To be considered one of the "loudest", the harmonic must have a relative amplitude ≥ 0.25 for one of the woods as listed in Table 3 Mean Relative Amplitudes. This means that for at least one wood the harmonic was present at a value no less than ¼ of the amplitude of the fundamental. Again, a shaded cell indicates that the maple has more of that harmonic.

Table 5 Ratio of Maple to Mahogany Mean Relative Amplitudes for Relative Amplitudes ≥ 0.25

	Harmonic Number										
String	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Average**
Low E	1.7606	1.0517	1.999	0.982							1.6
D	0.60320	0.5278									.5655
High E	1.4744	0.92794	1.2268	0.7289		0.8286		0.74648	0.4923		.9197
										Average:	**1.03**

These results are more consistent with the previous graphs. On average, the harmonics above the fundamental have a greater amplitude on the maple guitar for the low E string, whereas the mahogany has more for the D string. The mahogany has slightly more for the high E as well, but the end average of the three strings again shows that they balance each other out; one wood does not have more harmonics than the other on average, but the timbres are not the same.

MEASURES OF RELIABILITY

Coefficient of Variation

The coefficient of variation $c_v(n)$ of the relative amplitude of the n^{th} harmonic is defined as

$$c_v(n) = \frac{\sigma}{\mu}$$

where

$$n = harmonic\ number$$
$$\sigma = standard\ deviation\ of\ the\ relative\ amplitude\ rA_n$$
$$\mu = mean\ of\ the\ relative\ amplitude\ rA_n$$

The average coefficient of variation $\overline{c_v}(string)$ for a specified string was calculated by averaging the $c_v(n)$ for harmonics 2 through 11 such that

$$\overline{c_v}(string) = \frac{1}{10}\sum_{n=2}^{11} c_v(n)$$

where

$$n = harmonic\ number$$

This gives an overall picture how reliable results were for a single string. The values for each string per guitar are listed below in Table 6. On average, the rA_n of any harmonic was no greater than 8.43% from the mean of the population.

Table 6 Average Coefficient of Variation for Each String

Wood	String	$\overline{c_v}$
Maple	Low E	5.8%
Mahogany	Low E	3.6%
Maple	D	8.43%
Mahogany	D	4.46%
Maple	High E	6.05%
Mahogany	High E	8.25%

Tuning Accuracy

The frequency of a note is measured in cycles per second, or Hertz (Hz). Due to the logarithmic relationship between frequency and pitch, it is more useful to compare two pitches with cents (¢) rather than Hz. A cent is 1/100th of a half-step interval; there are always 100 cents in 1 half-step, but the amount of Hz in 1 half-step changes for each pitch. Therefore, cents are a more consistent measure for pitch comparison regardless of how high or low the frequency is. The difference in cents $\Delta¢$ between two frequencies f_1 and f_2 is defined by Suits from the Michigan Technological Institute as

$$\Delta¢ = 1200 \times \log_2\left(\frac{f_1}{f_2}\right)$$

where

$$f = frequency\ in\ Hz$$

Below in Table 7 the measured frequency of each string is given and compared to what the frequency for that note actually should be (Suits 2015). The difference in cents is also listed. The low E string had the greatest difference in pitch, with the D string and the high E string being much closer in pitch. The tuning discrepancy is a side effect of the difficulty of getting a physical instrument in perfect tune.

Table 7 Tuning Discrepancies

Wood	String	Mean Hz	Correct Hz	Δ¢
Maple	Low E	82.632	82.41	4.657
Mahogany	Low E	83.054	82.41	13.48
Maple	D	147.894	146.83	12.500
Mahogany	D	147.694	146.83	10.157
Maple	High E	330.089	329.63	2.4090
Mahogany	High E	329.808	329.63	0.93461

CONCLUSION

This study examined the timbre of tones produced by two guitars of identical construction but different woods, maple and mahogany. The timbres were compared by analyzing the differences in the amplitudes of harmonics produced by each wood. It was found that the maple guitar had more harmonics for the low E string, the mahogany had more harmonics for the D string, and neither guitar clearly had more harmonics overall for the high E. On average, across all three strings tested, neither guitar ended up being consistently brighter or warmer than the other; rather, the difference in timbre for each guitar varied depending on which string was being analyzed. Maple and mahogany were chosen for this experiment due to their purported extreme differences in timbre. These results indicate that while choosing between maple or mahogany as a guitar material can produce difference results, it is not clear that one wood is consistently "very bright" or "very warm", contrary to statements made by Sweetwater.

This study quantifies timbre as the ratio of the amplitude of harmonics relative to the amplitude of the fundamental frequency. It does not take into account the sustain of a note, which could also be used as a deciding factor when choosing a wood for a guitar. Even though this study did find differences in timbre, it would be useful to research whether or not one could actually hear the difference. Such research is outside the scope of this study; however, measuring the ability of one to perceive these differences is necessary to evaluate how different two timbres must be before they can be perceived as different.

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