Introduction

Regardless of one's origin, identity, upbringing, or circumstances, it can be most certainly said that motivation, passion, and drive exists in one form or another. Many rely on their passion to provide financial stability in the form of a job. Those that are adventurous enough to undertake the role of being a professional musician have only one way to improve their skills, thus increasing chances of a successful career: practice. Once a musician reaches a certain proficiency in their craft, they start to be more meticulous in practice. Strictly speaking in the example of saxophone players, manufacturers take advantage of this aspect by manufacturing and marketing countless brands of reeds, mouthpieces, and other accessories, often with bold and vague claims and description in how they differ. Players respond to this by testing out many different products in the endless search of the perfect combination. This ties into the motivation behind the research; it was conducted to quantify the differences, if any, of various reeds on the tone produced by a saxophone.

Due to the nature of the topic, a unique approach had to be taken when planning the experimental design. Because musical instruments are typically played by humans, this would undoubtedly introduce a level of variability to the results. To reduce experimental noise between the trials in an already sensitive experiment, an 'artificial blowing machine' was engineered, which allowed similar relative pressure and air speed across multiple trials. Experimentation was conducted by securing a fully assembled soprano saxophone into an artificial lip around the mouthpiece. This design allowed for the reeds to be changed out from trial to trial with ease. Using an air compressor, pressurized air was blown into the ‘artificial blowing machine’, then through the saxophone. The air vibrated the reed, causing a note to sound.

To most accurately represent the sound produced by a saxophone, it was decided that the harmonics would be quantified and analyzed. This involved using a microphone to record the note played by the instrument, followed by processing that data through software which visually displayed the sound produced as a fast Fourier transform (FFT) graph. FFT graphs are useful to show the amplitudes of the harmonics of a sound. These amplitudes across the fundamental and the first and second overtones, when compared, can show trends pertaining to a certain reed variety. With a significant difference in the amplitudes of the harmonics between the reeds, it can be concluded that various reeds do perform differently. Significance was determined through a statistical test as well as a descriptive analysis.

The findings can contribute to the scientific community as they illustrate the cause of why different reeds behave differently. Structural properties of an oscillating medium and sound go hand-in-hand to justify changes in the sound produced by a musical instrument. On a larger scale, the research can educate musicians to confidently make distinctions between different types of reeds, reducing the guesswork needed to find an ideal balance within equipment. Overall, the results from the research can be used to make the lives of woodwind players and musicians alike easier.

Review of Literature

Since the invention of the saxophone, there has always been a persistent battle to determine the ‘best’ mouthpiece and reed combination geared towards a specific sound, usually to emulate a specific player’s tone. Marketing pertaining to these products, especially recently, has increased confusion for consumers. Words like ‘bright’, ‘dark’, and ‘focused’, among many, have been used to describe the way a certain product will make a player sound. Many professional saxophonists swear by the type of equipment they use, and how it allows them to shape their sound effectively. Reeds come in many varieties; changes in thickness, and shape of the cane used occur across different brands. This analysis will investigate each of these variables in order to assess whether or not they can impact the sound produced by the saxophone.

It is vital to understand the fundamentals of reed behaviors and sound production before analyzing how different reeds change the sound outputted by a saxophone. Sounds are pressure waves traveling through a medium, typically air, which are the result of vibrations (Linder). Therefore, in order for a sound to be produced, an object needs to be oscillating. In the case of this research, this object is the reed, which vibrates at a certain rate. This rate is dependent on many factors such as: the player’s control, pressure, mouthpiece shape, number of keys pressed down, and whether the saxophone is free of misalignments. Changes in the reed’s vibration can alter the sound of the saxophone. Once the reed starts vibrating, it causes the air within the instrument to vibrate and move in the form of pressure waves (Mathias). These pressure waves travel through the instrument and get amplified until they exit the saxophone, producing the sound that is heard by listeners.

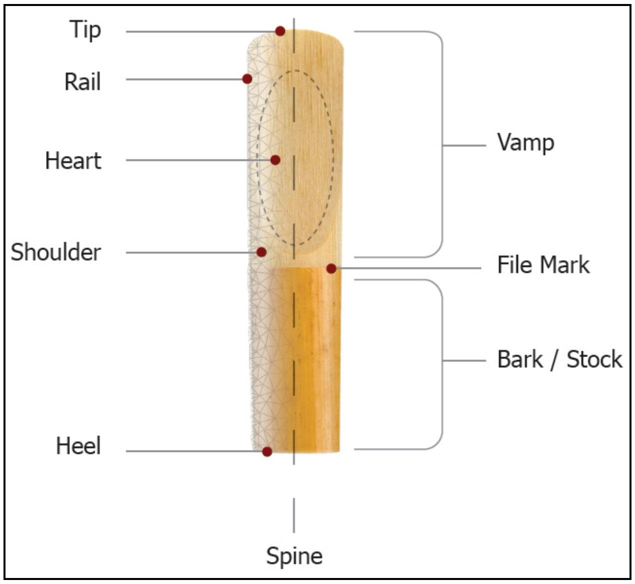

Figure 1. Reed Anatomy Chart. Image from Normans Musical Instruments Group, “Reeds – What Size / Strength Do I Need?,” 2013

Figure 1, above, shows a diagram of a reed which is broken down into two main components. Most reeds are made of a cane tree, which is then filed into the final shape. The stock of the reed which is attached to the mouthpiece of the saxophone using a ligature. The other half is the vamp of the reed which is filed down, and is the part that vibrates in order to create the sound produced by the saxophone. Some reeds have vamps that are filed down thinner, and many have different shapes. Also, most reeds opt for a shoulder that is filed down as seen in the above Figure 1, though some do not contain a filed shoulder. All of these differences in the shape and thickness of the reed can alter the reed’s vibrational patterns (“Reeds”).

Within the sound of any musical instrument, or pitch in nature for that matter, lies a series of pitches also known as harmonics. Particularly, in addition to the main pitch being heard, or the fundamental pitch, there also lies overtones, which sound above the prominent pitch at certain ratios depending on the instrument. The saxophone is a conical instrument; due to its properties, it is a closed pipe, operating similarly to a clarinet or flute in terms of its harmonics.

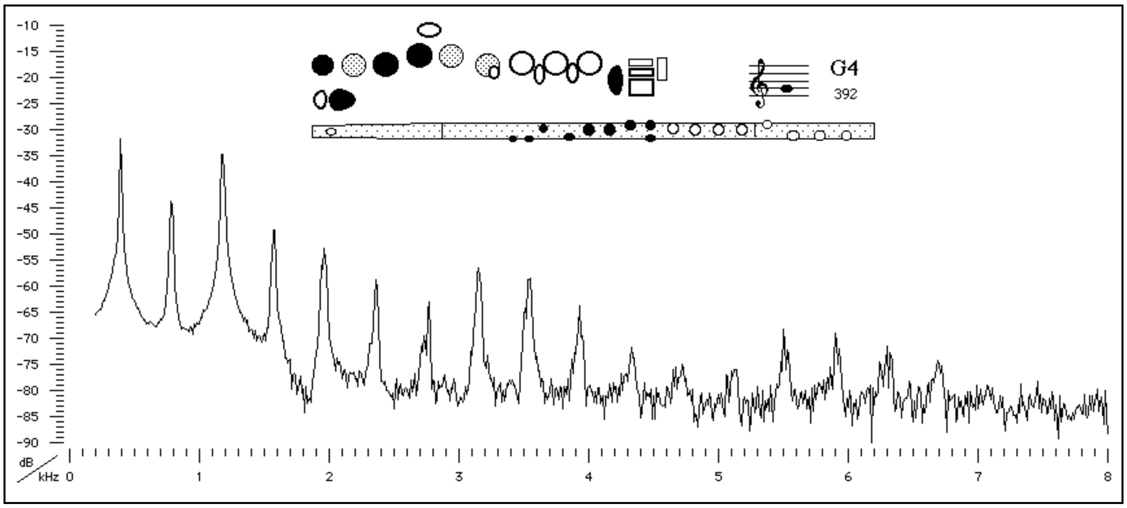

Figure 2. Sound Spectrum of the Note G4 on the Flute. Image from The University of New South Wales, “Flute Acoustics,” 2001

Closed pipe instruments produce harmonics at integer multiples o f the fundamental frequency. For example, in the above Figure 2, the note G4 of the flute (another closed pipe instrument) produces a fundamental frequency of 400 Hz, so the first overtone (or second harmonic) will be at a frequency of 800 Hz. A fundamental frequency of 400 Hz means that the air in the instrument is vibrating with a pattern that repeats 400 times a second (Wolfe).

The varying strength overtones in the harmonic series, known as the instrument’s sound spectrum, are a main factor contributing to an instrument’s sound. Using the example of a reed, variations in thickness, stiffness, and other factors can alter the vibrational pattern of a reed, therefore allowing certain harmonics to be prominent over others. A sound can be analyzed through amplitudes of these harmonics relative to one another, depicting a particular quality (Goldner). Descriptions of musical sound qualities is a solely subjective field; however it is generally agreed upon that a brighter tone has more prominent upper harmonics, and that a darker tone has more prominent middle to low harmonics (Petiot). In the realm of saxophone playing, the bright versus dark analysis is a common discussion when comparing jazz mouthpiece, reed, and saxophone combinations. Analyzing the sound spectrums of different reeds will provide fundamental evidence for the difference between them, allowing accurate investigation into timbre changes.

Previous research was done on this topic in 2017 by a group of people from McGill University. They conducted a perceptual study using a panel of 10 musicians to assess 20 reeds of the same brand based on three factors. The musicians looked for differences in the softness, brightness, and perceived quality of the sound, which are subjective measurements. With these criteria, the panel found differences between the reeds overall. This gives some evidence to show that reeds do impact the sound being produced, even between reeds that are from the same box (Petiot).

As previously mentioned, the research conducted for this experiment will provide a quantitative analysis regarding the effect of reed qualities on sound production. With the knowledge obtained from experimentation, certain tonal attributes will be associated with particular reed types. The research will provide insightful information for all saxophonists, amateur and professional alike.

Problem Statement

Problem:

Do different types of saxophone reeds change the sound quality produced by a saxophone?

Hypothesis:

There will be a difference in the reeds in terms of wave amplitude and harmonic production, leading to different sound qualities.

Data Measured:

The independent variable will be the style of reed tested, particularly Vandoren V16, Java Red, Java Green, and ZZ reeds. The dependent variable that will be analyzed is the response of each reed in terms of their harmonic amplitudes. A microphone and Vernier LabQuest will be used to create FFT visualizations of the sound produced by the saxophone. Amplitudes of the fundamental and first two overtones will be averaged and processed through a statistical test to determine significance, if any.

Experimental Design

Materials:

Vandoren Jazz Soprano Saxophone Java Red Reed
Vandoren Jazz Soprano Saxophone Java Green Reed
Vandoren Jazz Soprano Saxophone V16 Reed
Vandoren Jazz Soprano Saxophone ZZ Reed
Yamaha 4C Soprano Saxophone Mouthpiece
Rovner Soprano Saxophone Ligature
Laptop (with Logger Pro Software)
TI-Nspire CX Calculator
Air Compressor
Cup of Water
Paper Towel
Saxophone and Logger Pro Assembly (Appendix A)
Artificial Blowing Machine (Appendix B)
Artificial Lip (Appendix C)

Procedures:

1. Assemble the saxophone and set up Logger Pro software (see Appendix A).

2. Construct the Artificial Blowing Machine (see Appendix B).

3. Construct the Artificial Lip (see Appendix C).

4. Randomize trials by using the integer function on the TI-Nspire CX calculator using values 1-4, to randomize the type of reed used. For example, if a 3 is generated by the calculator, then a V16 reed will be used for that trial.

5. Wet the reed that was selected through the randomization by submerging it in a cup of water for 5 seconds, then pat with paper towel to remove excess water.

6. Place this reed on the mouthpiece so that the top of the reed is flush with the top of the mouthpiece.

7. Slide the ligature over the mouthpiece, and tighten it so that the reed is secure in place.

8. Secure the artificial lip onto the reed, then place this securely into the opening of the artificial blowing machine, making sure that the seal between the artificial lip and the rubber toilet flapper is tight.

9. Start data collection on the Logger Pro software, then turn on the air compressor at 22 psi until the saxophone plays a note for 1 second.

10. Save the results of the trial and label according to the type of reed.

11. Record the amplitude of the fundamental tone as well as the first and second overtones present in the FFT graph, and sort the data according to each reed in preparation for post-analysis.

12. Repeat steps 5 through 11 forty times to test all the reeds.

<u>Diagram</u>:

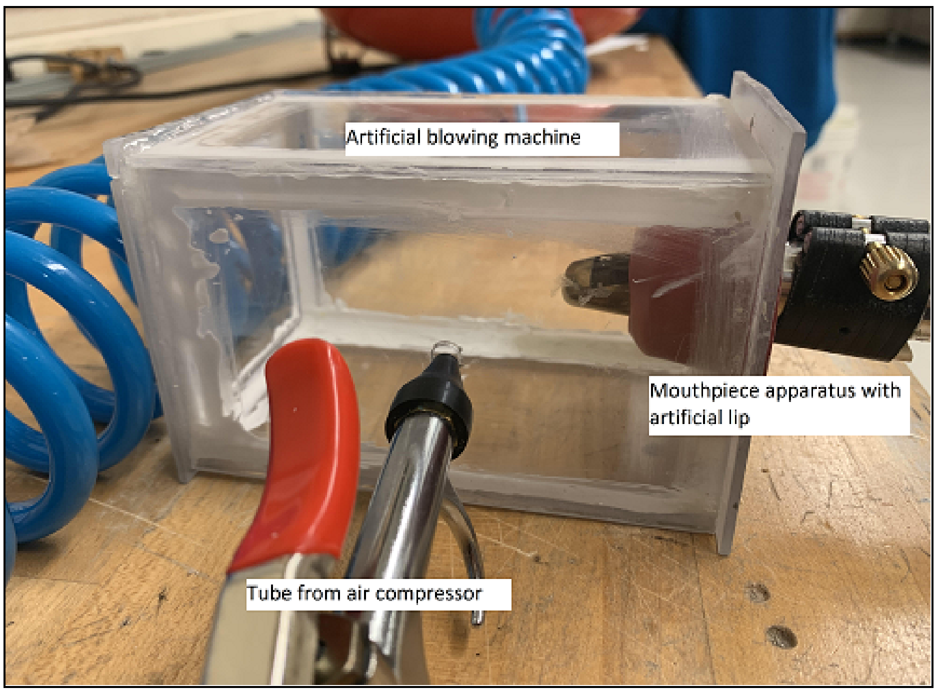

Figure 3. Artificial Blowing Machine to Saxophone Connection

Figure 3 above displays the blowing machine connected to the saxophone. As seen, the neck and mouthpiece are held securely and airtight by the assembly of the machine, through the use of the rubber. The mouthpiece is held under the piece of foam, or the artificial tongue. Air will flow freely through the machine and through the saxophone. This image was taken before the tape was installed, as to show the components of the machine.

Data and Observations

Table 1
Amplitude of the Fundamental and First Two Overtones for the Java Red Reed Type

Trial	Java Red (Amplitude)			
	Fundamental	Overtone 1	Overtone 2	Average
1	2.86	1.50	2.38	2.25
2	3.58	0.86	1.04	1.83
3	0.85	0.55	0.29	0.56
4	2.60	0.98	0.48	1.35
5	4.21	1.60	1.19	2.33
6	3.49	1.66	0.52	1.89
7	2.99	1.51	0.46	1.65
8	2.30	1.87	0.55	1.57
9	1.91	2.46	0.84	1.74
10	1.46	2.29	1.12	1.62
Average	2.63	1.53	0.89	1.68

Table 1, above, shows the amplitudes of the fundamental and first two overtones for each trial of the Java Red reeds, alongside the means of each harmonic and the mean of all harmonics across each trial. In regards to the other three types of reeds, the amplitude of the fundamental and first overtone of the Java Red reeds were the lowest, and the second overtone was the second lowest. This resulted in the Java Red reeds having the lowest overall amplitude value of 1.68.

Table 2
Amplitude of the Fundamental and First Two Overtones for the Java Green Reed Type

Trial	Java Green (Amplitude)			
	Fundamental	Overtone 1	Overtone 2	Average
1	3.18	3.21	0.91	2.43
2	2.53	1.82	0.58	1.64
3	2.44	2.15	0.71	1.77
4	2.61	2.96	0.59	2.05
5	1.49	1.85	0.72	1.35
6	4.51	2.32	0.54	2.46
7	5.18	2.33	1.62	3.04
8	3.24	2.19	0.98	2.14
9	5.83	1.05	0.58	2.49
10	4.26	1.97	0.49	2.24
Average	3.53	2.19	0.77	2.16

As seen in Table 2, above, the Java Green reeds produced fundamental and first overtone amplitudes that are the second lowest when compared to the other reeds that were tested, while producing the overall lowest second overtone amplitude. The total average of the first three harmonics for each trial that was run for the Java Green reeds can be seen as 2.16, which is the second lowest among the reeds that were tested.

Table 3
Amplitude of the Fundamental and First Two Overtones for the ZZ Reed Type

Trial	ZZ (Amplitude)			
	Fundamental	Overtone 1	Overtone 2	Average
1	5.03	1.91	1.20	2.71
2	3.83	3.92	1.41	3.05
3	6.63	1.85	1.12	3.20
4	4.43	2.96	1.20	2.86
5	4.72	2.99	1.14	2.95
6	5.29	1.66	1.78	2.91
7	6.55	2.23	1.55	3.44
8	6.44	2.31	1.31	3.35
9	5.83	2.34	1.72	3.30
10	5.60	3.00	1.79	3.46
Average	5.44	2.52	1.42	3.12

Table 3, above, shows the data collected from the from the ZZ reed trials. It can be seen that the fundamental and second overtones had the highest overall amplitudes, while the first overtone produced the second highest in respect to the first overtones of the other reeds. This reed produced the highest overall amplitude value of 3.12.

Table 4

Amplitude of the Fundamental and First Two Overtones for the V16 Reed Type

Trial	V16 (Amplitude)			
	Fundamental	**Overtone 1**	**Overtone 2**	**Average**
1	4.34	1.22	1.21	2.26
2	4.28	3.82	0.65	2.92
3	6.10	2.49	0.78	3.12
4	4.98	3.07	0.51	2.85
5	6.11	2.89	0.58	3.19
6	4.46	2.23	1.87	2.85
7	3.33	1.92	1.58	2.28
8	3.75	3.08	1.55	2.79
9	6.81	3.39	0.79	3.66
10	4.88	2.99	2.70	3.52
Average	4.90	2.71	1.22	2.95

As seen in Table 4, above, the V16 reeds produced fundamental and second overtones that had the highest amplitude when compared to the other reeds that were tested. These reeds also produced the highest overall first overtone amplitude. The mean of the amplitude between all trials for all three harmonics was found to be 2.95, which is the second highest when compared to the other three types of reeds.

Table 5
Java Red Observations

Trial	Observation
1	Large outlier of 2.38 for the second overtone.
3	Low value of 0.85 for the fundamental.

In Table 5, above, it can be observed that there are not many observations for the Java Red style of reed. Most of these trials went as planned, except for the outlier of the first trial.

Table 6
Java Green Observations

Trial	Observation
1	Large outlier of 3.21 for the first overtone.
7	Large outlier of 1.62 for the second overtone.
6-10	First overtone values are substantially higher than the trials 1-5, but the second and second overtone values stayed about the same as the first 5.
9	Low outlier of 1.05 for the first overtone.

Table 6, above, shows the observations that were recorded for the Java Green Reeds over the span of the experiment. This style of reed seemed to have the most variation and it had the most amount of outliers across the three overtones.

Table 7
ZZ Observations

Trial	**Observation**
2	High value of 3.92 for the first overtone.
9	Connection between artificial lips and the rubber flapper opened up slightly causing a small leak in the artificial blowing machine's airtight seal.

The ZZ observations, as seen in the above Table 7, did not have many observations as most trials went as planned. A leak in trial 9 could have caused some variation in the data.

Table 8
V16 Observations

Trial	**Observation**
1	Low value of 1.22 for the second overtone.
10	The artificial blowing machine expanded slightly more than usual when pressurized during this trial.

Table 8, above, shows the observations that were recorded for the V16 reed type. Overall this type of reed had a large amount of variation but there was only one outlier.

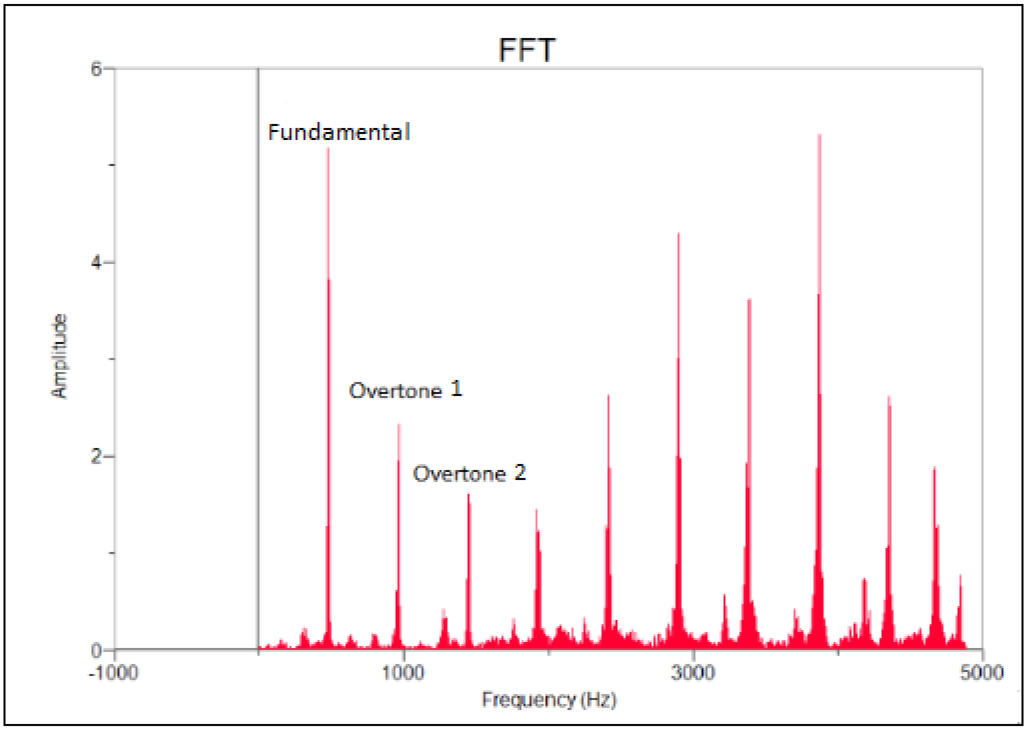

Figure 4. Trial 7 of the Java Green Reeds

In Figure 4, above, the FFT graph of the sound produced by the saxophone with a Java Green reed is shown. It can be observed that the harmonics occur at about every 475 Hz. There is little obstruction in the graph, and the harmonics are very clearly shown. This trial was done in a closet within a workshop with negligible outside noise.

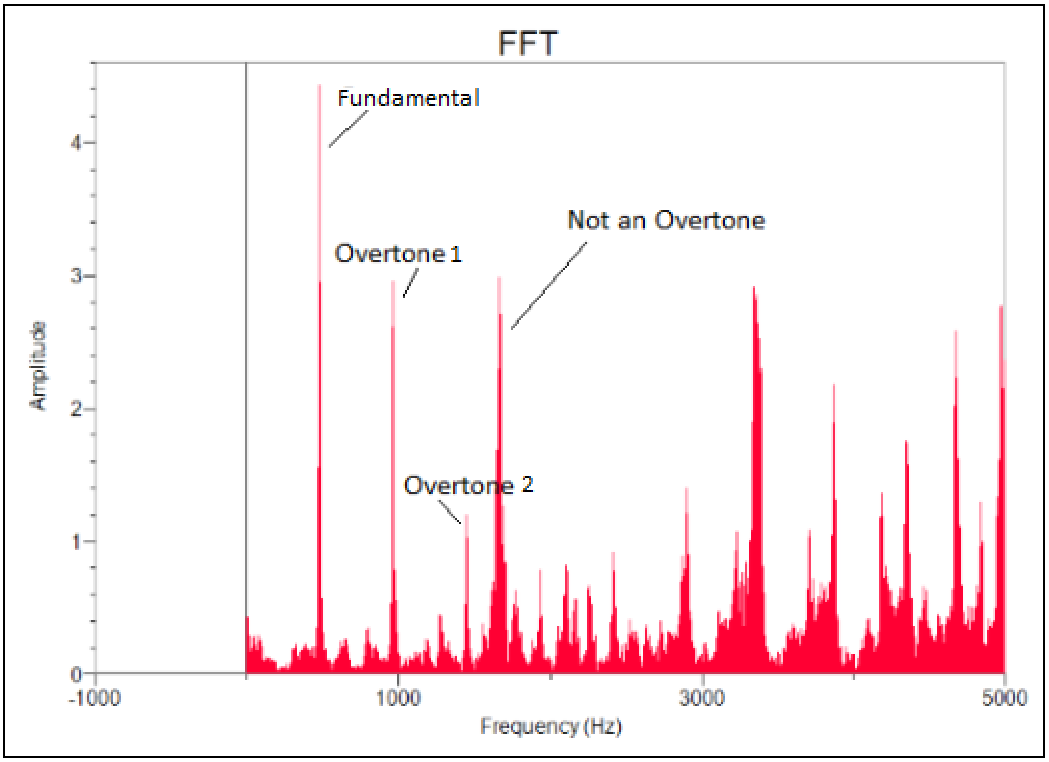

Figure 5. Trial 4 of the ZZ Reeds

As shown in Figure 5, above, the fourth trial of the ZZ reeds had a lot of obstruction and it contained random spikes after the third overtone that were not overtones. One of these false spikes can be seen at about 1600 Hz. Though, this is outside of the range of focus in the experiment, and regardless of these spikes showing up or not the first three harmonics still stayed at about the same values. This trial was done in a basement on a different day than the trial shown in Figure 4.

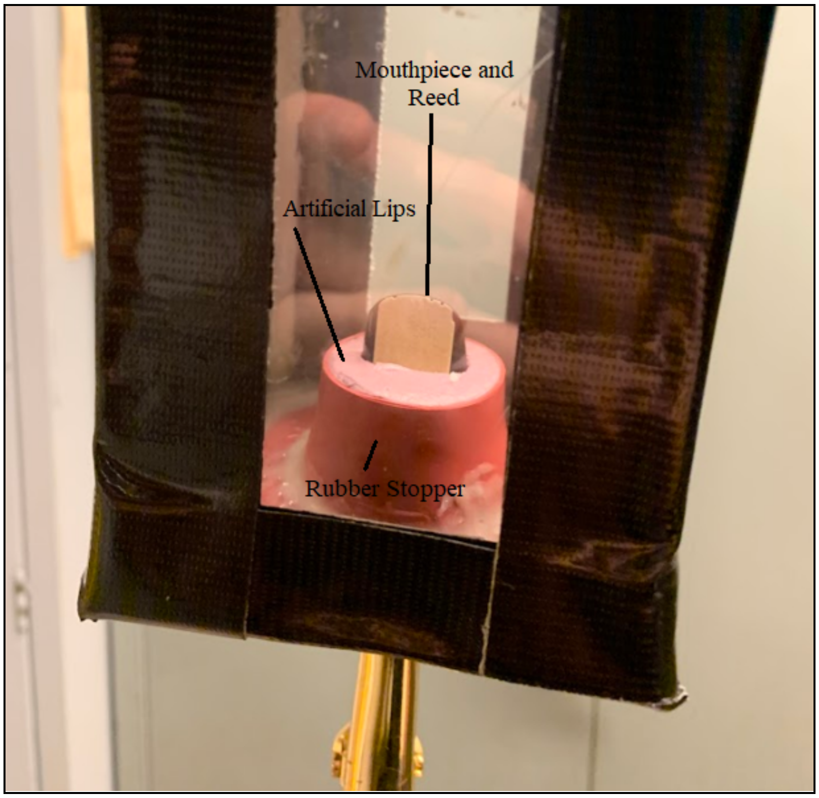

Figure 6. Reed and Artificial Lips Inserted into the Artificial Blowing Machine

There were some places of concern when it came to keeping the artificial blowing machine airtight. Two of these instances can be seen in the above Figure 6. One of which was the connection between the artificial lips and the reed, where the artificial lips had small imperfections and holes around the reed that caused some air to leak through. The other point of concern was the connection between the rubber flapper and the artificial lips. In some cases, such as trial 9 of the ZZ style reeds, the pressure in the box would be just enough for air to force its way through the lip of the rubber flapper. Since the purpose of the box is to blow at the same pressure every time in order to achieve a consistent note, this caused some issues in regards to consistency of the trials. This, however, was only observed for one trial, and the data for this trial was similar to the rest of the ZZ reed type trials.

Data Analysis and Interpretation

The experiment described in this paper is a comparative experiment which displays the differences in performance of four different styles of saxophone reeds available on the market. The data that was collected was in the form of frequency tables that show the strength of a sound's harmonics. With the aid of a device that was engineered for this project, air was blown through a saxophone to vibrate one of the given reeds, producing sound. This sound was recorded for half of a second, and instantly inputted into graphing software. The same saxophone, mouthpiece, estimated pressure, and note were used as constants. Trials were randomized to ensure that bias from the setup or researchers would not affect the overall results. Ten randomized trials were conducted for each reed to limit uncontrollable lurking variables. This also helps to reduce confounding in the form of ambient noise and sound reflection, as it should affect all groups equally. Descriptive statistics and an Analysis of Variance (ANOVA) test was conducted to determine significance.

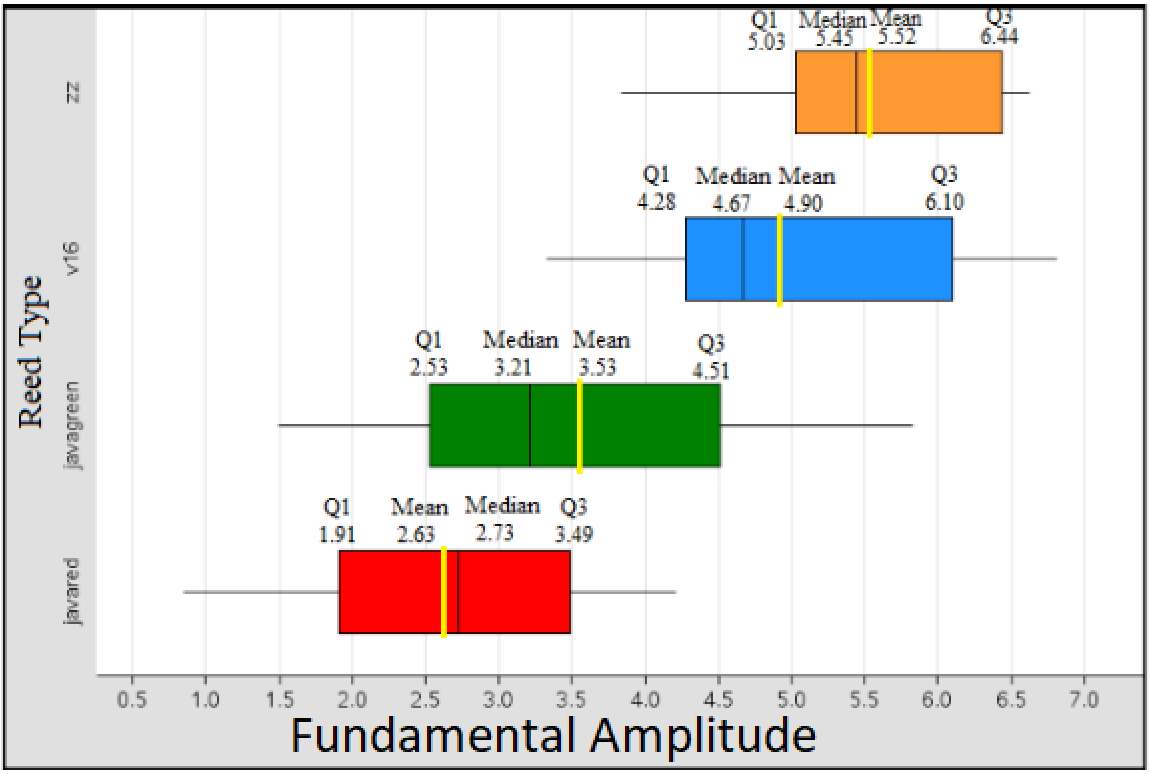

Figure 7. Strength of the Fundamental Across All Reed Types

Figure 7 above shows box-and-whisker plots that represent the data for the strengths of the fundamental for each reed. This figure particularly refers to the values recorded for the strength of the fundamental, or its amplitude. Looking at the plots cumulatively, it is evident that all of the reeds overlap. This could suggest that there is no significant difference between reeds in this set. Despite this, there is some distinction between reeds. There is a general pattern where, going from bottom to top, all values regarding the boxes increase, as well as the mean. The minimum values and maximum values for each reed type also increase in the same manner, except for the greater 25% of data for the ZZ reed. No outliers existed for the data concerning the fundamental.

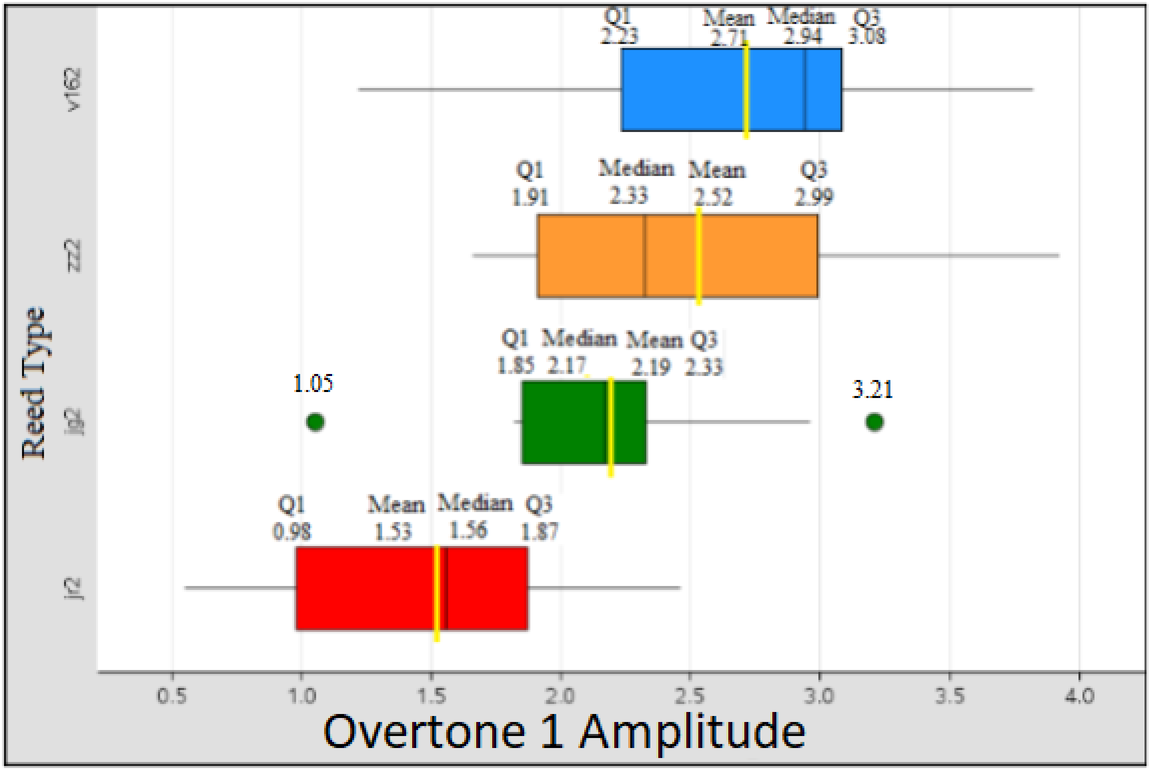

Figure 8. Strength of the First Overtone Across All Reed Types

Figure 8, above, shows plots of the data collected across all reeds for the first overtone. Similarly to the fundamental in Figure 7, there is overlap across all reed types. Particularly in the first overtone, it seems that the Java Green reed's box falls almost entirely within the ZZ's box, indicating great overlap. The Java Green reed also had two outliers, but they were roughly equidistant from the mean of the set. The first two overtones both had great ranges for each reed. The same notable pattern from Figure 7 stays true here; from bottom to top, the middle 50% of data and the median all showed an increasing trend.

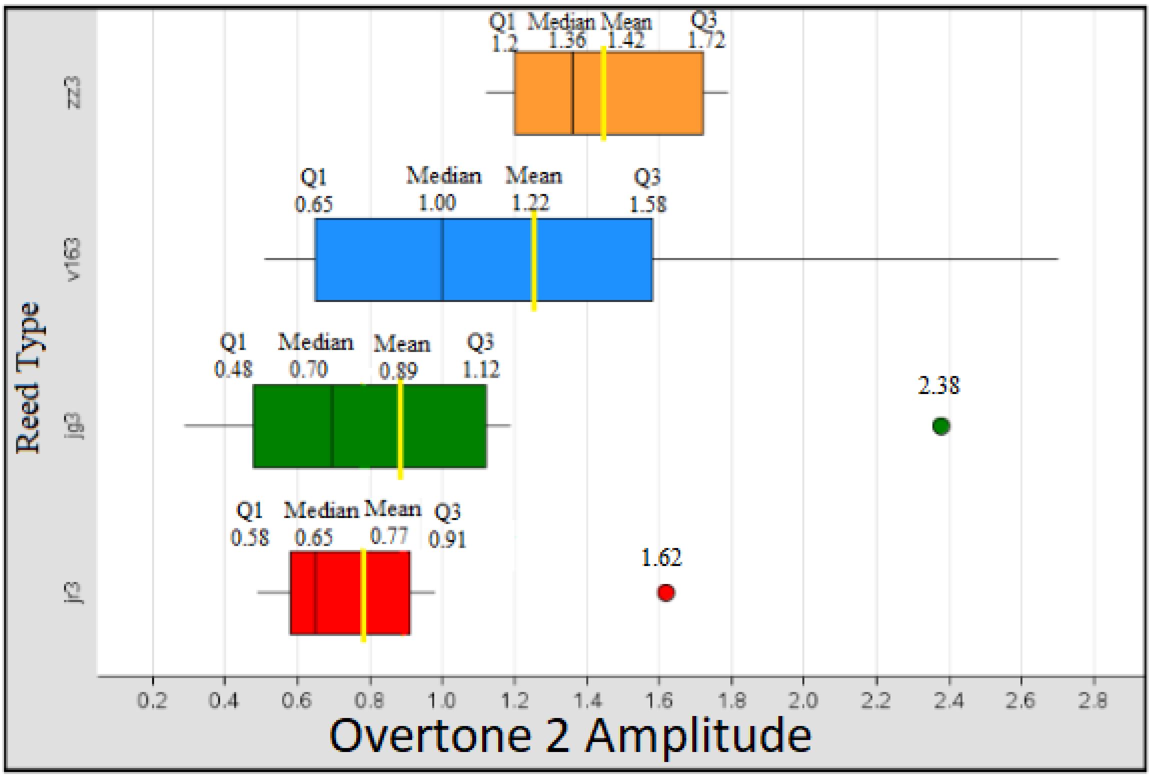

Figure 9. Strength of the Second Overtone Across All Reed Types

Figure 9, above, shows the data collected across all four reed types for the second overtone in the form of box-and-whisker plots. It is evident from this representation that the Java Red reed's data fell entirely within the middle 50% of data of the Java Green reed, which is significant overlap. It can be observed that all of the Java Red data is contained within the interquartile range of the Java Green data, which is a significant amount of overlap. The V16 reed has an extremely large range of its second overtone strength. There were two outliers, one in the Java Red reed and one in the Java Green reed. The pattern from previous figures still stands when referring to the means, as they continued to increase going from bottom to top.

As seen through Figures 7-9, all the boxplots within each respective overtone overlapped in some way, suggesting that the differences between each reed style may not be significant. To verify this, an Analysis of Variance (ANOVA) Test for each overtone was conducted. This test was chosen because there are four populations of different reed types, and the purpose of this experiment is to find out if the different types of reeds have a statistically significant difference in the sound produced by a saxophone. The formula is explained in Appendix E.

H_o: $\mu_{\text{Java Red}} = \mu_{\text{Java Green}} = \mu_{V16} = \mu_{ZZ}$

H_a: Not all $\mu_{\text{Java Red}}$, $\mu_{\text{Java Green}}$, μ_{V16}, and μ_{ZZ} are equal.

Figure 10. Hypotheses for ANOVA Test

The Figure 10, above, shows the null and alternative hypothesis used in the ANOVA test. The null hypothesis states that there is no difference between the mean amplitudes of harmonics across the different types of reeds. The alternative hypothesis states that not all means are equal to one another, and that there is a significant difference between them.

In order to conduct the ANOVA Test, all 3 of the assumptions must be met. The first assumption is that each of the populations (Java Red, Java Green, V16, and ZZ) must be simple random samples. This assumption was met because all of the trials were randomized using the Random Integer function on the TI-Nspire. The second assumption states the standard deviations must be similar. A common rule of thumb for the ANOVA statistical test is that the largest standard deviation must not be more than twice the smallest standard deviation. The third assumption requires that each sample comes from a population that has a normal distribution. This was not able to be determined when looking at the box plots of the data in Figures 7-9, so normal probability plots were created. These can be seen in Figures 14-16, where most of the data did not veer far off of the normal probability plot. Most of the box plots were skewed and some had outliers, but nothing was severe enough to conclude that the data was not normally distributed.

"Title"	"One−Variable Statistics"	"_____"	"_____"	"_____"
"$\bar{x}$"	3.527	2.625	4.904	5.521
"Σx"	35.27	26.25	49.04	55.21
"Σx^2"	141.306	78.3925	251.73	311.898
"$sx := s_{n-1}x$"	1.37066	1.02666	1.11743	0.887186
"$\sigma x := \sigma_n x$"	1.30032	0.973974	1.06009	0.841658
"n"	10.	10.	10.	10.
"MinX"	1.49	0.85	3.33	3.83
"Q_1X"	2.53	1.91	4.28	5.03
"MedianX"	3.21	2.73	4.67	5.445
"Q_3X"	4.51	3.49	6.1	6.44
"MaxX"	5.83	4.21	6.81	6.63
"$SSX := \Sigma(x-\bar{x})^2$"	16.9084	9.48625	11.2378	7.08389

Figure 11. Statistical Calculations of Java Green, Java Red, V16 and ZZ for the Fundamental with Standard Deviations

Figure 11 shows the calculations for Java Green, Java Red, V16 and ZZ for the fundamental as seen in all of the columns respectively. In the fifth row, the standard deviations are boxed, which support the third assumption. In order for the data to show almost equal variance, the largest standard deviation must not be more than twice the smallest standard deviation. Their standard deviations were 0.89, 1.03, 1.12 and 1.37. Since the highest standard deviation of 1.37 is not more than twice of 0.89 (1.78), the second assumption can be considered met.

"Title"	"One−Variable Statistics"	"_____"	"_____"	"_____"
"$\bar{x}$"	2.185	1.528	2.71	2.517
"Σx"	21.85	15.28	27.1	25.17
"Σx^2"	51.0139	26.6408	78.6358	67.6789
"$sx := s_{n-1}x$"	0.602923	0.604884	0.759737	0.693302
"$\sigma x := \sigma_n x$"	0.571983	0.573843	0.72075	0.657724
"n"	10.	10.	10.	10.
"MinX"	1.05	0.55	1.22	1.66
"Q_1X"	1.85	0.98	2.23	1.91
"MedianX"	2.17	1.555	2.94	2.325
"Q_3X"	2.33	1.87	3.08	2.99
"MaxX"	3.21	2.46	3.82	3.92
"$SSX := \Sigma(x-\bar{x})^2$"	3.27165	3.29296	5.1948	4.32601

Figure 12. Statistical Calculations of Java Green, Java Red, V16 and ZZ for the First Overtone with Standard Deviations

Figure 12 shows the calculations for Java Green, Java Red, V16 and ZZ for the first overtone, with the standard deviations boxed. Their standard deviations were 0.60, 0.61, 0.69 and 0.76. Since the highest standard deviation of 0.76 is not more than twice of 0.60 (1.20), the second assumption is met.

"Title"	"One−Variable Statistics"	"_____"	"_____"	"_____"
"$\bar{x}$"	0.772	0.887	1.222	1.422
"Σx"	7.72	8.87	12.22	14.22
"Σx^2"	6.988	11.2211	19.4014	20.8716
"$sx := s_{n-1}x$"	0.337994	0.610411	0.704632	0.268899
"$\sigma x := \sigma_n x$"	0.320649	0.579086	0.668473	0.2551
"n"	10.	10.	10.	10.
"MinX"	0.49	0.29	0.51	1.12
"Q_1X"	0.58	0.48	0.65	1.2
"MedianX"	0.65	0.695	1.	1.36
"Q_3X"	0.91	1.12	1.58	1.72
"MaxX"	1.62	2.38	2.7	1.79
"$SSX := \Sigma(x-\bar{x})^2$"	1.02816	3.35341	4.46856	0.65076

Figure 13. Statistical Calculations of Java Green, Java Red, V16 and ZZ for the Second Overtone with Standard Deviations

Figure 13 shows the calculations for Java Green, Java Red, V16 and ZZ for the second overtone, with the standard deviations boxed. Their standard deviations were 0.27, 0.34, 0.61 and 0.70. The highest standard deviation of 0.70 is higher than twice the standard deviation of the lowest (0.54), but the ANOVA test is not too sensitive to violating this assumption, and the value is not too much higher, so the statistical test still can be run.

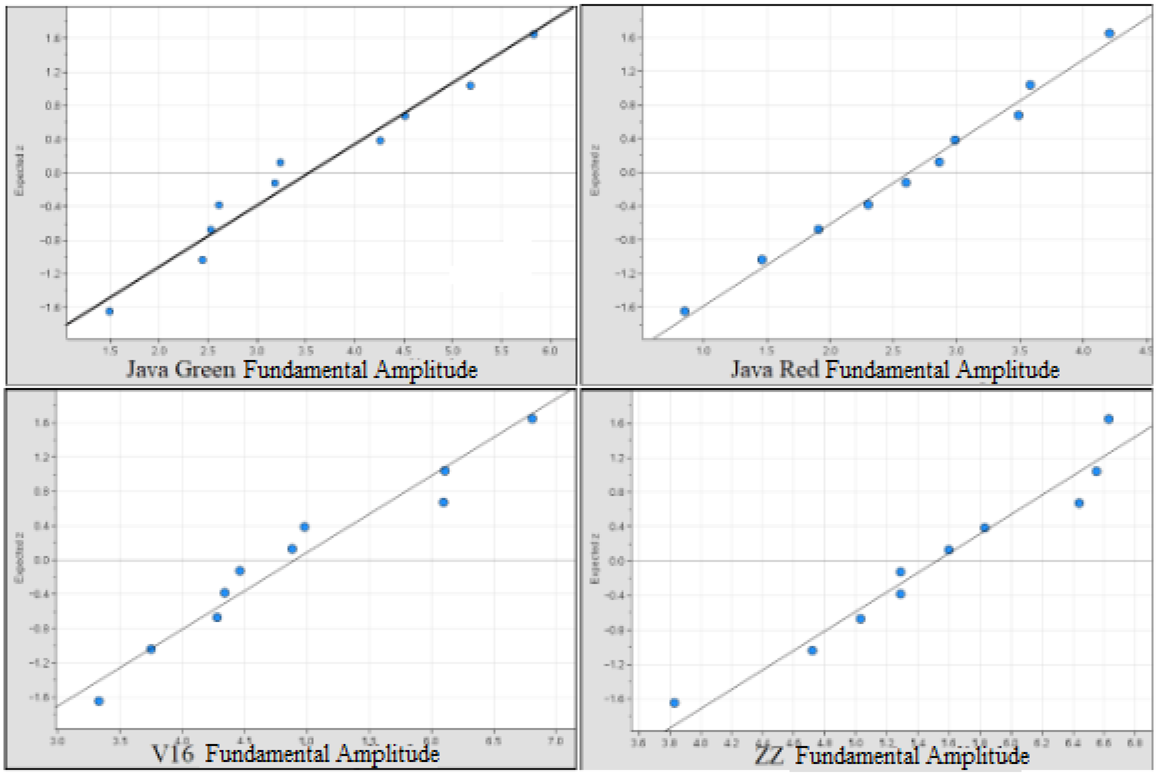

Figure 14. Fundamental Normal Probability Plots for Java Green, Java Red, V16 and ZZ Reed Types

Figure 14 displays the data for the first four reeds for the fundamental, each on their respective normal probability plot and line. It does not seem that there are any significant outliers, and the line seems to represent the data sufficiently well for each set. The data for the fundamental across all reed types can be considered normal.

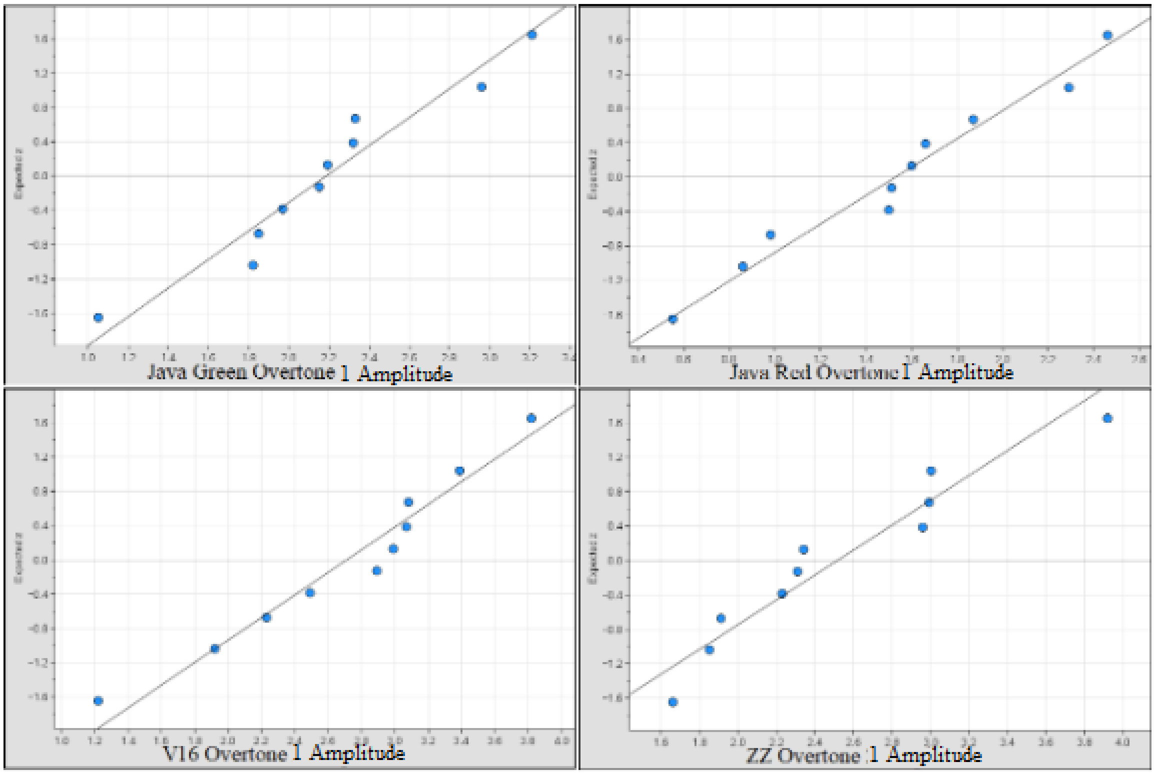

Figure 15. First Overtone Normal Probability Plots for Java Green, Java Red, V16 and ZZ Reed Types

Figure 15, above, shows the normal probability plots generated for all reeds respectively in relation to the first overtone. Like the fundamental, it seems as if there are any extreme outliers, and all data points are relatively close to the line. Therefore, the data pertaining to the first overtone can be deemed normal.

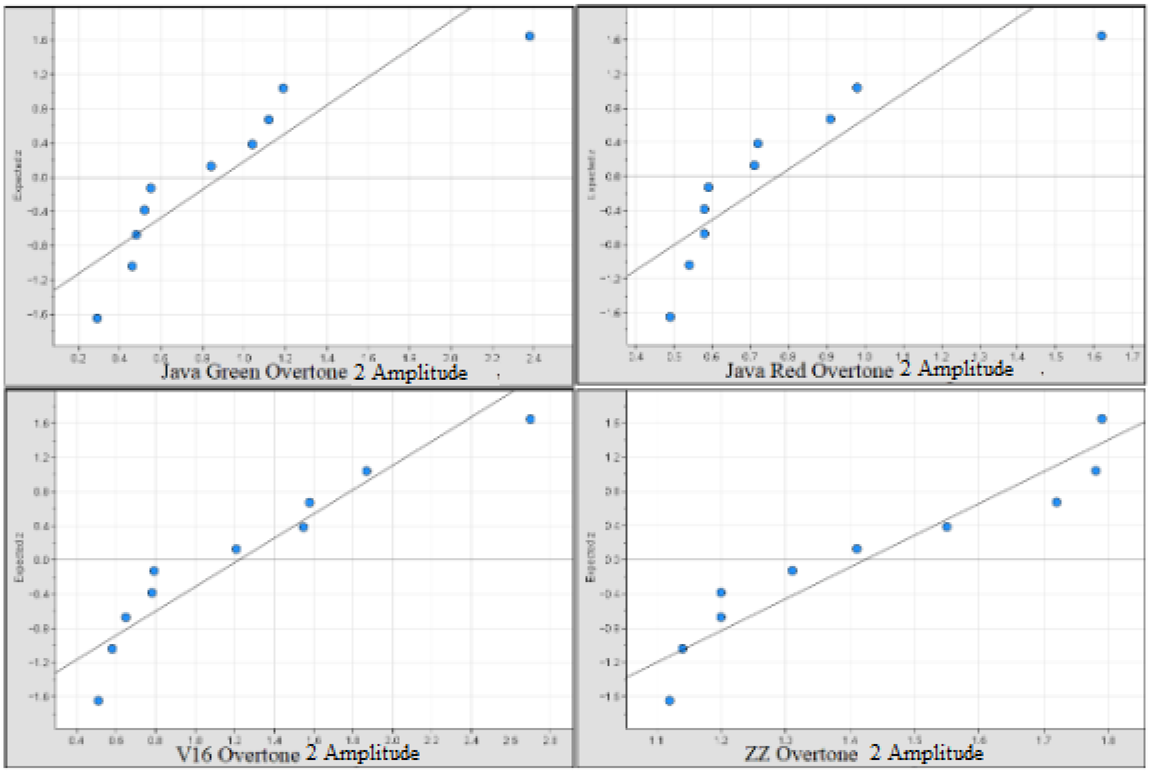

Figure 16. Second Overtone Normal Probability Plots for Java Green, Java Red, V16 and ZZ Reed Types

Figure 16 shows the data pertaining to the second overtone, and normal probability plots were created in the same manner. It seems as if there are a few outliers, particularly in the Java Green and Java Red sets. Looking past them, the rest of the data pieces are represented by the expected z line quite well. There is sufficient representation here to deduce that the second overtone's data sets are normal.

"Title"	"ANOVA"
"F"	13.852
"PVal"	0.000004
"df"	3.
"SS"	51.6178
"MS"	17.2059

Figure 17. ANOVA Test Results for the Fundamental

Figure 17 shows the results of the first ANOVA test that was run. Sample calculations for the ANOVA statistical test are available in Appendix E below. Because the P-value, 4.0×10^{-6} is less than the alpha level of 0.05, the null hypothesis is rejected. There is strong evidence that, for the fundamental, the means of the different types of reeds are statistically significantly different from one another. For the fundamental, there is a near 0 percent chance of having the same means occur by chance alone if the null hypothesis is true.

"Title"	"ANOVA"
"F"	6.02407
"PVal"	0.001959
"df"	3.
"SS"	8.07498
"MS"	2.69166

Figure 18. ANOVA Test Results for the First Overtone

Figure 18 shows the results of the second ANOVA test that was run; calculations were made the same way as the first. Because the P-value, about 0.002, is less than the alpha level of 0.05, the null hypothesis is rejected. There is strong evidence that, for the fundamental, the means of the different types of reeds are statistically significantly different from one another. For the first overtone, there is about a 0.2 percent chance of having the same means occur by chance alone if the null hypothesis is true.

"Title"	"ANOVA"
"F"	3.39971
"PVal"	0.027983
"df"	3.
"SS"	2.69169
"MS"	0.897229

Figure 19. ANOVA Test Results for the Second Overtone

Figures 19, above, displays the results of the last ANOVA test. The P-value for the second overtone was 0.028. Since it is less than the alpha level of 0.05, the null hypothesis is rejected. There is about a 2.79 percent chance that the same means would occur again by chance alone if the null hypothesis is true.

After analyzing the trials and testing for a significant difference, the ANOVA results showed that there is a statistically significant difference in overtone amplitudes between each reed type for each harmonic, meaning the reeds performed significantly differently. This allows definitive conclusions to be drawn regarding the certain acoustic behavior of each reed. It can be assumed that, due to the variations in the reed’s structure, vibrational patterns change. This causes the varying amplitudes in the harmonics, effectively changing the sound.

Conclusion

The purpose of this experiment is to determine if there is a difference in sound produced between four different varieties of saxophone reeds commonly available on the market. It was hypothesized that, by using different reeds, the sound produced by a saxophone would be different, giving each reed quantifiable characteristics. After utilizing descriptive statistics and the ANOVA test of significance to compare findings of each reed, the hypothesis was accepted.

Extensive work was put into creating an experimental design that would facilitate research of this sort. In order to test minuscule differences in reed behavior, the inherent variability that results from a person trying to replicate processes through a musical instrument had to be eliminated. To accomplish this, an artificial blowing machine was engineered to guide a specific amount of air from a compressor to control the vibration of a reed through a saxophone, pictured in Figure 3. The note played by the artificial blowing machine was recorded with a microphone that was connected to a computer with fast fourier transformation (FFT) analyzing software, creating a visualization of a sound wave to allow statistical interpretation.

Using the FFT graphs, a few key features of a sound wave were analyzed. When a sound is produced, especially in the case of musical instruments, there are multiple notes that are sounded at the same time which play at certain intervals of a fundamental frequency, depending on the instrument. These are also known as overtones. By comparing the amplitudes of the overtones produced by each reed, a definitive conclusion could be reached on whether or not different reeds have different timbral properties. The first three overtones were analyzed specifically to maintain simplicity. At each, the amplitude of the sound wave was recorded, and box-and-whisker plots were created from this data to analyze the statistical differences, if any, between each of them. Data points and averages across each reed type were also compared. Visible in Figures 7-9, there was some noticeable overlap between the reed's corresponding box plots over all of the overtones. The ranges and five-number summaries suggested, however, that there was a pattern, and this pattern stayed mostly consistent going from the first to third overtone. Since the data did not show an obvious difference in the overtones of each reed, statistical testing was done to see if there was actually a statistically significant difference in the amplitudes of respective overtones.

Three analysis of variance (ANOVA) tests were run across each of the three overtones comparing the four different types of reeds. After running the three tests, the P-values of each came out to be less than the alpha level of 0.05. This means that, for each overtone, there was strong evidence that the different reeds possessed different tendencies, as seen by the amplitudes. Since the prevalence of certain overtones can identify a particular sound timbre, it can be concluded that different reeds change the sound produced by a saxophone, thus accepting the stated hypothesis.

Before determining how different reeds can affect the sound produced by a saxophone, it is necessary to understand how reeds can produce sound in the first place. When air is blown past a reed at a certain pressure, it causes the reed to vibrate, which then causes the air around the reed to form pressure waves (Linder). These pressure waves then travel and get amplified throughout the saxophone until they exit out of the end and carry towards the listener's ear (Mathias). This produces the sound that is heard.

The nature of how reeds can affect the sound that is produced by a saxophone can be narrowed down to a couple of things. Since the sound produced is determined by the vibration of a reed, the physical properties of the different reeds can alter its sound. For example, the thickness and shape can change the way in which a reed vibrates.

Saxophone reeds in particular have filed and unfiled options. Filed reeds, like the name suggests, are filed down in the middle of the reed between the bark and the vamp. The four reeds that were tested in this experiment were the Java Red, Java Green, V16, and ZZ varieties. The Java Red is the only variety of the four that is filed. The rest are unfiled, but have a few key differences. The heart of the reed, displayed in Figure 1, is a very important component of how a reed is cut. The general rule of thumb is that: as the amount of cane present in the heart increases, then more air and pressure are needed by the player to produce a sound ("Choosing"). The three unfiled varieties, listed from the most to the least amount of heart, are Java Green, V16, and ZZ. In theory, the unfiled reeds will take more air pressure to produce a sound than the filed reeds will, due to the fact that there is more cane.

A key property of a cane reed, or any vibrating medium to produce a sound for that matter, is that there are micro-fluctuations in the vibrational pattern. These micro-fluctuations act in tandem with the material composition of the instrument, causing the mechanical waves to propagate in different ways and produce different amounts of harmonics in the sound (Polotti). This is the reason why certain instruments have different sound spectrums and timbral qualities from others, making flutes, for example, sound different from trumpets. A visualization of a sound spectrum can be seen in Figure 2.

Micro-fluctuations also contribute to the response, or the pressure needed to make a sound, of a particular reed. The Java Red reed is the thinnest of the four tested alongside having the least amount of heart and being the only filed reed. These factors working together suggest that, in theory, the Java Red reed should vibrate the easiest. This, in turn, leads it to be more prone to micro-fluctuations, and overall, produce higher overtones (Wolfe). A harder reed, such as the unfiled ZZ, will have the thickest heart, and as such, will be less likely to have a high amount of overtones.

This is reflected in the findings of the research, as well. After analyzing the averages of each reed over all three overtones, it was found that the ZZ reed had the highest proportion of first overtone amplitude to the second and third overtones, and the V16, Java Green, and Java Red followed, in order of decreasing proportion. Despite the ZZ and V16 reeds having higher overall numbers than the Java reeds for the second and third overtones, the proportion to the first overtone is a more accurate measure of the overall quality of the sound. This agrees with other research that has been conducted by others; when a sound has a greater prevalence of higher overtones in relation to the first, then it is perceived as a brighter tone, and the opposite occurs for a darker tone (Almeida).

The accuracy of the experiment could have been compromised due to a poor experimental design and procedure. In order to facilitate the procedures, an artificial blowing machine was constructed as a human would be too inconsistent. The process to initially produce a sound using the engineered blowing machine included lots of trial and error. One major issue was that the air pressure was not the exact same every time as the air compressor was at a range of anywhere between 15-25 psi. When looking at the artificial lips (Figure 26), it can be concluded that the mouthpiece and reed were not in the same position every time, affecting the reed's ability to vibrate. If more of the mouthpiece was inside of the box, the reed would vibrate more freely, and vice versa. The angle of the mouthpiece also could not be held exactly constant every time. This presented some amount of confounding as this could have an effect on the amplitude of the resulting sound waves.

Across each trial, the manner in which sound was produced was quite different. In some trials, the saxophone made a sound right after the air compressor was turned on, while in others, the mouthpiece needed to be adjusted a little bit.

Humidity also played a large role in the performance of reeds. If a reed was dry, it can not play. Trials were recorded in two different environments, one being in a hot, relatively humid closet at a school, and the other being a cold and dry basement. This could affect the performance of reeds, and the ease to vibrate, meaning more pressure essentially would be needed to make the reed vibrate. Saxophones, being made of brass, respond differently depending on the ambient temperature. On top of this, the saxophone, a vintage Yamaha soprano saxophone, was in slight disrepair. The pads, although functional, were in need of replacement, and while this is a small influence, it could have still affected the results of the experiment.

It is important to note that the quality and timbre of a sound is represented by a combination of all of its harmonics. Seeing as how only the fundamental and first two overtones were tested, future research could implement the analysis of higher harmonics.

The properties of synthetic reeds could also be tested. These types of reeds could vibrate in different patterns when compared to the cane reeds tested in this experiment. Potentially, this experiment could be ran with 3D printed reeds, in which, certain thicknesses and shapes could be examined more closely.

In order to get more consistent data, the artificial blowing machine could be better constructed, and could use more robust materials and sealing techniques. The re-engineering of the artificial lip could be beneficial as to accommodate for consistent placement of the mouthpiece and exposure to the inside of the box. Also a pressure limiter could be used to more precisely control the pressure going into the box. Another part of the saxophone equipment that is often discussed is the mouthpiece and ligature, both of which have great debates over whether they make a difference or not. Different types of both could be tested in future iterations of this experiment.

This research can be used in order to aid individuals in understanding how different reeds do actually affect the sound of the notes they play. If a musician is attempting to accomplish a particular tone, they can test out different reeds more confidently, eliminating the guesswork that marketing establishes.

Appendix A: Assembling the Saxophone and Data Collection Setup

Appendix A involves the assembly of the saxophone, as well as how to setup the Logger Pro Software. This is a preliminary procedure and is not to be repeated for every trial.

Materials:

Yamaha 4C Soprano Saxophone Mouthpiece
Yamaha YSS-675 Soprano Saxophone
Hercules Saxophone Stand
Microphone
LabQuest Mini
Laptop (with Logger Pro Software)

Procedures for Assembling the Saxophone:

1. Carefully twist the mouthpiece onto the neck of the saxophone until it is 0.5 inches from the base of the cork.

2. Twist the neck into place and tighten the neck screw.

3. Place the entire saxophone onto the Hercules saxophone stand.

4. Clamp the microphone to the bell of the saxophone.

5. Plug the microphone into the LabQuest Mini, then connect the LabQuest Mini into the laptop with Logger Pro software.

6. Set up the Logger Pro software so that it records sound using the microphone, and change the settings so that it will automatically start capturing data once the sound pressure increases above the arbitrary value of 2.5. Then set the data collection duration to 0.25 seconds at 0.0001 seconds per sample.

7. Then add a Fast Fourier Transformation (FFT) graph, which presents the amplitudes of the harmonic series of the sound.

<u>Diagrams</u>:

Figure 20. Mouthpiece Assembly

The figure pictured above shows the reed, ligature, and mouthpiece assembly. The top of the reed is sitting flush with the top of the mouthpiece, and the ligature is securely holding everything into place.

Figure 21. Saxophone Assembly with Stand

Above, the assembled saxophone is pictured. The mouthpiece is on the neck, which is tightened into the saxophone. A Hercules stand is holding the saxophone up.

Appendix B: Building the Artificial Blowing Machine

Appendix B describes the construction of the artificial blowing machine, involving processing the materials, and constructing and sealing the container.

Materials:

Razor Blade	Lexan Polycarbonate Plexiglass (⅛ in)
Drill Bit (⅛ in)	Drill
Minute Weld Instant-Setting Epoxy	Jigsaw
Rubber Toilet Flapper	Sandpaper (120 Grit)
Air Compressor with Pressure Controller	Quick-Setting Silicone
Masking Tape	Gorilla Tape

Procedures:

1. Using the jigsaw, cut out four 3x5 inch pieces from lexan polycarbonate plexiglass. Then cut out two 3x3 inch pieces of the same plexiglass.

2. Sand down each piece of plexiglass up to a ¼ inch from all edges on one side using the 120 grit sandpaper. This will help the epoxy and caulking adhere to them better.

3. Mix the two parts of the Minute Weld instant-setting epoxy, then apply it to the 5 inch edges of the rectangular-face plexiglass pieces, and assemble them as seen in Figure 22. Use masking tape to hold the pieces together as the epoxy cures.

4. Wait for the epoxy on the rectangular-face plexiglass pieces to cure, then apply the epoxy to the edges of one of the square-face pieces of plexiglass, followed by adhering it to one side of the remaining two open faces of the prism.

5. In the other square piece of plexiglass, drill a hole in its center that is 1.5 inches wide in diameter, as seen in Figure 23. Smooth out the inner edges of the hole with 120 grit sandpaper.

6. Using a razor blade, make small incisions in the parts of the rubber toilet flapper that will make contact with the square piece of plexiglass, as seen in Figure 23, then adhere the two using the epoxy.

7. Using the drill and the ⅛ inch drill bit, drill a ⅛ inch hole in the center of one of the rectangular pieces of plexiglass.

8. Once all of the previously laid epoxy has dried, seal all of the inside edge connections of the box using the quick-setting caulking.

9. Attach the square plexiglass piece with rubber toilet flapper onto the last open face of the mechanism using epoxy, with the extended part of the toilet flapper on the inside. This can be seen in Figure 26.

10. Seal every connection again from the outside using more epoxy followed gorilla tape. This will ensure an airtight mechanism.

<u>Diagrams</u>:

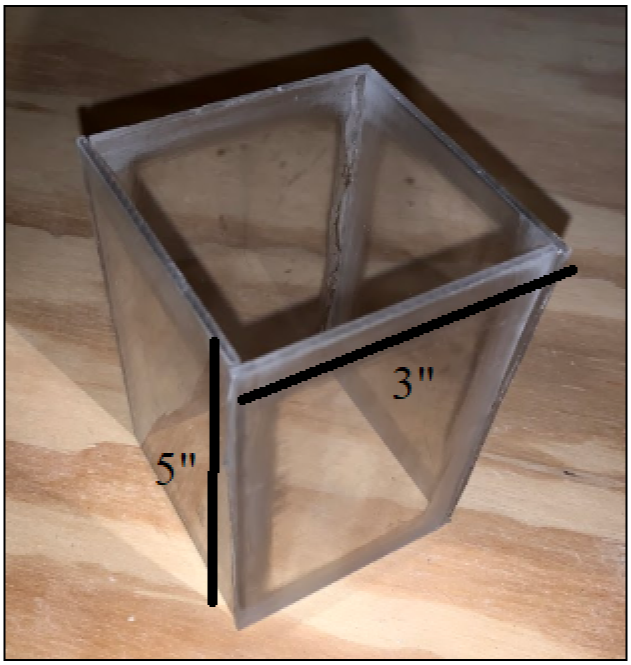

Figure 22. Assembly of 3x5 Inch Rectangular Pieces of Plexiglass

The picture above displays the appearance of the assembly without the last face on, which will be the opening where the mouthpiece of the saxophone is inserted.

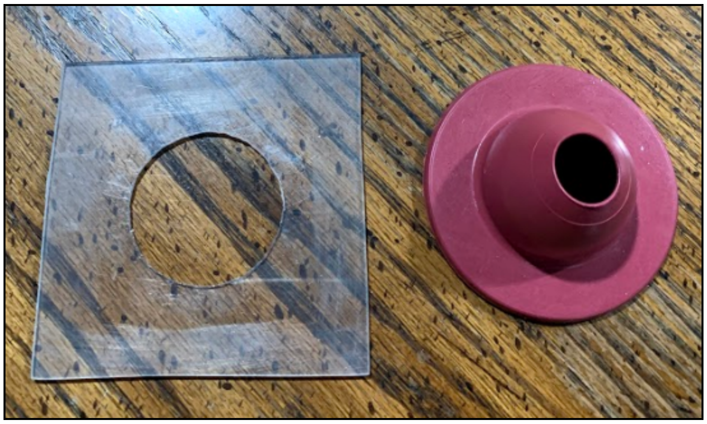

Figure 23. 3x3 Inch Piece of Plexiglass with 1.5 Inch Diameter Hole and Toilet Flapper

Figure 23 above shows the two pieces needed for the construction of the last face of the rectangular assembly. Both pieces are serrated with a razor blade so that the epoxy adheres better, helping to keep the box airtight.

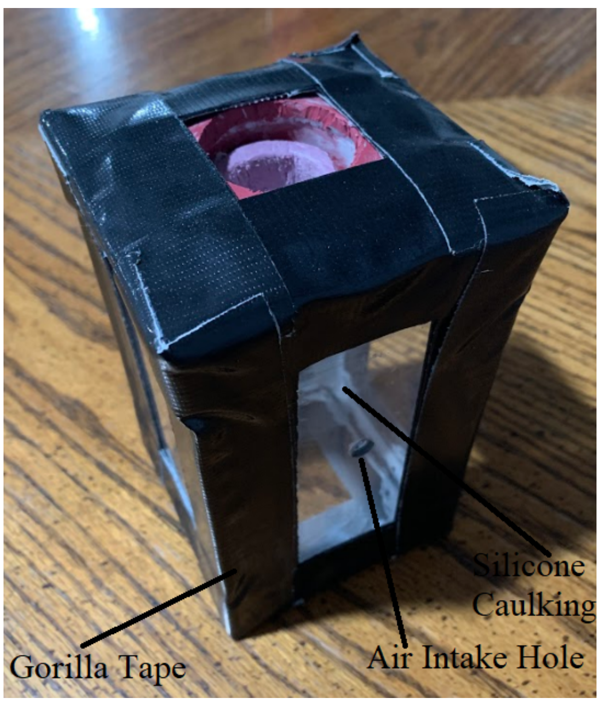

Figure 24. Artificial Blowing Machine

Figure 24 displays the artificial blowing machine and its components. The entire machine is lined with airtight silicone caulking, as well as gorilla tape on the outside to ensure no leakage of air. The air intake hole is sealed when the air compressor nozzle is pressed into it.

Appendix C: Building the Artificial Lip

Appendix C explains the construction of the artificial lip. This piece gives the same amount of pressure to the reed every time a trial is run, in order to maintain consistency and to emulate a human's mouth when playing.

Materials:

Polyurethane Foam (1.5 in)
Single Edged Razor Blade
Sandpaper (120 Grit)

Procedures:

1. Cut a 2x2 inch piece of the polyurethane foam out using the single edged razor blade.

2. Using the 120 grit sandpaper, sand the the 2x2 inch piece of foam down until it is barely large enough to fit into the end of the toilet flapper, as seen in Figure 25.

3. Cut a hole in the foam piece that is just big enough so that it fits around the mouthpiece and reed of the saxophone half an inch from its tip, shown in the below Figure 26.

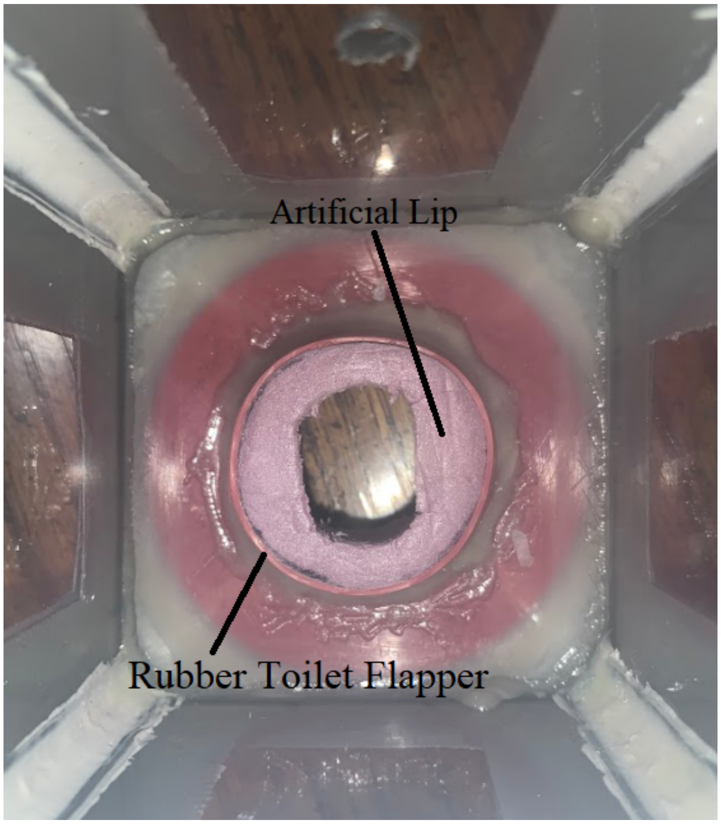

Figure 25. Rubber Toilet Flapper with Artificial Lips Inserted

The artificial lips must fit perfectly into the rubber toilet flapper in order to keep the artificial blowing machine airtight through a frictional seal. Figure 25 shows what the artificial lips would look like when placed in the rubber toilet flapper of the artificial blowing machine. Since the rubber toilet flapper is flexible, it suits well to expand around the sides of the artificial lip and create a seal.

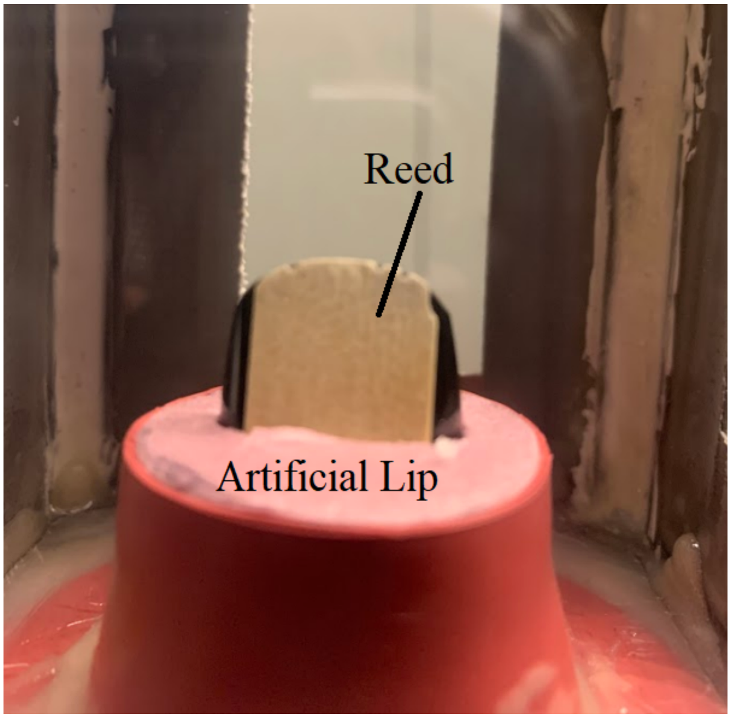

Figure 26. Mouthpiece Assembly Inserted into the Artificial Lip

Figure 26, above, shows the connection between the mouthpiece assembly and the artificial lip when inside of the artificial blowing machine. The artificial lip fits tightly around the mouthpiece assembly a half an inch from the tip of the reed.

Appendix D: Calculating the Standard Deviation

In this appendix, a formula for the standard deviation is provided alongside a calculation for the standard deviation of one point.

$$\sigma = \sqrt{\frac{\sum (x-\bar{x})^2}{n}}$$

Figure 27. Standard Deviation Formula

Figure 27 shows the standard deviation formula. Standard deviation is used to measure the distance of the data from the mean. The variables in the formula include σ: standard deviation, $\sum$: capital sigma means "the sum of", x: sample data point, $\bar{x}$: mean, and *n:* sample size.

$$\sigma = \sqrt{\frac{(4.51-3.53)^2}{1}}$$

$$\sigma = 0.\ 98$$

Figure 28. Standard Deviation Example

Figure 28 shows a sample calculation using the standard deviation formula shown in Figure 27. The example calculates the standard deviation for Trial 6 of the fundamental for the Java Green reed, which turned out to be 0.98

Appendix E: ANOVA Test Formulas

Appendix E provides step by step calculations used to find the ANOVA test results for the fundamental. Formulas are shown followed by the substitution and answer.

$$F = \frac{MSG}{MSE}$$

Figure 29. F Statistic Formula

This is the formula for the F statistic for the ANOVA test. MSG is the mean square group, or the variation among sample means between each population. MSE is the mean square error, or the variation among individuals in all samples in each population. When the F statistic is large, the corresponding P-value is small.

$$\bar{x} = \frac{n_1\bar{x}_1 + n_2\bar{x}_2 + n_3\bar{x}_3 + n_4\bar{x}_4}{N}$$

Figure 30. Mean Used in ANOVA Formula

This formula is the weighted x bar used in the MSG and MSE formulas to find the F statistic. N is the total number of samples taken; n is the sample size of each respective population; $\bar{x}$ is the respective sample mean.

$$\bar{x} = \frac{10(3.53) + 10(2.63) + 10(5.44) + 10(4.90)}{40}$$

$$\bar{x} = 4.144$$

Figure 31. Example ANOVA Mean Calculation

This figure shows the numbers from the experiment plugged into the x bar formula. The final mean is approximately 4.144.

$$MSG = \frac{n_1(\bar{x}_1 - \bar{x})^2 + n_2(\bar{x}_2 - \bar{x})^2 + n_3(\bar{x}_3 - \bar{x})^2 + n_4(\bar{x}_4 - \bar{x})^2}{I - 1}$$

Figure 32. MSG Formula

This figure shows the formula to find the mean square group. I is the number of populations; n is the respective sample size; $\bar{x}_n$ is the sample mean; $\bar{x}$ is the weighted mean shown in Figure 30, calculated in Figure 31.

$$MSG = \frac{10(3.53-4.144)^2 + 10(2.63-4.144)^2 + 10(5.44-4.144 + 10(4.90-4.144)^2}{10-1}$$

$$MSG = 17.23$$

Figure 33. Example MSG Calculation

This figure shows the corresponding numbers from the trials plugged into the equation. The mean square group is approximately 17.23.

$$MSE = \frac{(n_1-1)s_1^2 + (n_2-1)s_2^2 + (n_3-1)s_3^2 + (n_4-1)s_4^2}{N-I}$$

Figure 34. MSE Formula

This figure shows the formula to find the mean square error for the ANOVA test. N is the total number of observations; I is the number of populations; n_x is the respective sample size; s_n is the respective sample standard deviation (refer to Appendix A to calculate).

$$MSE = \frac{(10-1)(1.371)^2 + (10-1)(1.027)^2 + (10-1)(1.117)^2 + (10-1)(.887)^2}{40-4}$$

$$MSE = 1.24$$

Figure 35. Example MSE Calculation

This figure shows the numbers from the trials plugged into the formula to find the mean square error. The value is approximately 1.24.

$$F = \frac{MSG}{MSE}$$

$$F = \frac{17.23}{1.24}$$

$$F = 13.87$$

$$df = \frac{I-1}{N-I}$$

$$df = \frac{3}{39}$$

Figure 36. Solving for the F Statistic and Interpreting for the P-Value

The figure above shows how the previous formulas were combined and divided to get the F statistic. The F statistic is about 13.87, close to the calculator version of 13.85 The degrees of freedom in ANOVA is actually a fraction, where the numerator is the number of populations -1 and the denominator is the number of samples by the number of observations. This fraction is not reduced. This fraction is used in the F distribution table to find the P-value, where the numerator decides the column and the denominator decides the row in the table. The P-value for this case was 4.0×10^{-6} (calculated through TI-Nspire software for higher accuracy).

Appendix F: Professional Contact

This appendix will show the communication with the professional contact.

Name: Lori Goldner

Title: Professor

Organization: University of Massachusetts Amherst Physics Department

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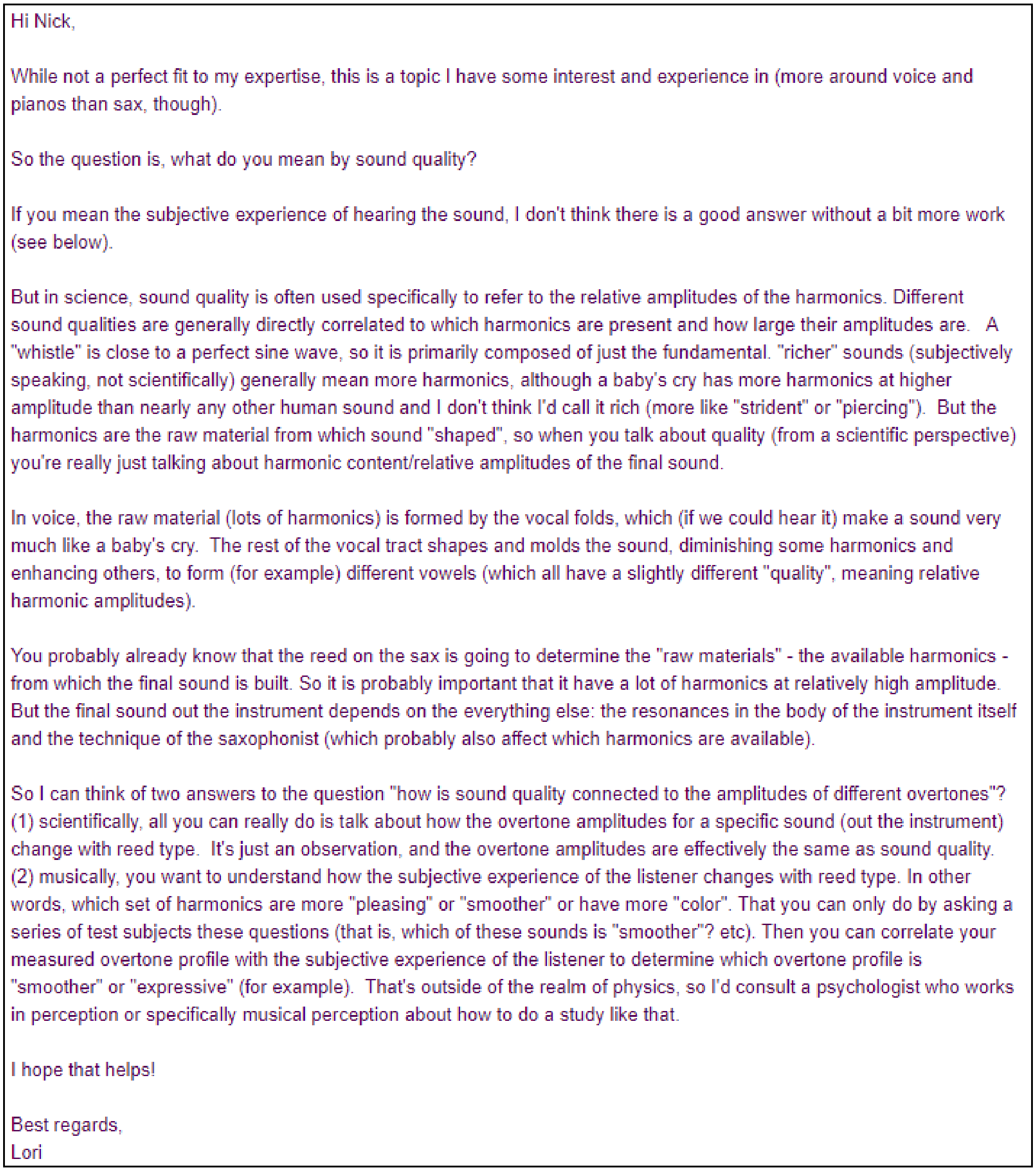
Email: lgoldner@physics.umass.edu

Mailing Address: 1126 Lederle Graduate Research Tower



Hi Nick,

While not a perfect fit to my expertise, this is a topic I have some interest and experience in (more around voice and pianos than sax, though).

So the question is, what do you mean by sound quality?

If you mean the subjective experience of hearing the sound, I don't think there is a good answer without a bit more work (see below).

But in science, sound quality is often used specifically to refer to the relative amplitudes of the harmonics. Different sound qualities are generally directly correlated to which harmonics are present and how large their amplitudes are. A "whistle" is close to a perfect sine wave, so it is primarily composed of just the fundamental. "richer" sounds (subjectively speaking, not scientifically) generally mean more harmonics, although a baby's cry has more harmonics at higher amplitude than nearly any other human sound and I don't think I'd call it rich (more like "strident" or "piercing"). But the harmonics are the raw material from which sound "shaped", so when you talk about quality (from a scientific perspective) you're really just talking about harmonic content/relative amplitudes of the final sound.

In voice, the raw material (lots of harmonics) is formed by the vocal folds, which (if we could hear it) make a sound very much like a baby's cry. The rest of the vocal tract shapes and molds the sound, diminishing some harmonics and enhancing others, to form (for example) different vowels (which all have a slightly different "quality", meaning relative harmonic amplitudes).

You probably already know that the reed on the sax is going to determine the "raw materials" - the available harmonics - from which the final sound is built. So it is probably important that it have a lot of harmonics at relatively high amplitude. But the final sound out the instrument depends on the everything else: the resonances in the body of the instrument itself and the technique of the saxophonist (which probably also affect which harmonics are available).

So I can think of two answers to the question "how is sound quality connected to the amplitudes of different overtones"?
(1) scientifically, all you can really do is talk about how the overtone amplitudes for a specific sound (out the instrument) change with reed type. It's just an observation, and the overtone amplitudes are effectively the same as sound quality.
(2) musically, you want to understand how the subjective experience of the listener changes with reed type. In other words, which set of harmonics are more "pleasing" or "smoother" or have more "color". That you can only do by asking a series of test subjects these questions (that is, which of these sounds is "smoother"? etc). Then you can correlate your measured overtone profile with the subjective experience of the listener to determine which overtone profile is "smoother" or "expressive" (for example). That's outside of the realm of physics, so I'd consult a psychologist who works in perception or specifically musical perception about how to do a study like that.

I hope that helps!

Best regards,
Lori

Figure 37. Email Reply from Lori Goldner

Figure 37, above, shows the reply that was sent by Lori Golder. She presented knowledge that allowed for a better understanding of harmonics and how they relate to sound quality. On top of this she described what exactly sound quality is in respect to this experiment.

Works Cited

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