Effects of Vowel Modification in Singing:
An Acoustic Investigation of the High Soprano Range

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1. Introduction

In the realm of singing, specifically for sopranos, there is an acoustic phenomenon that occurs as the sung frequency increases: the vowels sound closer together, or more alike, as perceived by the listener. The reason is that the frequency is higher, and therefore the spacing between the harmonics is greater. When singing lower notes, the acoustic effects are almost speech-like; the resonances of the vocal tract and the fundamental frequency are completely separate. However, what happens if the fundamental frequency gets so high that it actually goes into the range of the resonances of the vocal tract, and there is nothing left to amplify? For a bass who is singing a low G, their harmonics might only be spaced out by 100 Hz, and they therefore can take advantage of the many resonances of the vocal tract going up to the thousands. Even if they are not musically in tune, it is more likely that some of the harmonics will fall close to the vocal tract resonances. The vocal tract resonances produce formants, or bands of energy concentrations, that give information about vowels. Different positions of the vocal tract result in different amplified frequencies, making vowels sound distinctive. Since different vowels have different formant patterns, for a soprano, certain vowels lend themselves more easily to singing higher notes. The German composer Richard Wagner actually recognized this; he either knowingly or unknowingly took into account the acoustics of the high soprano in his text settings, using certain vowels more often for high notes than low notes. Since the harmonics are more spaced apart for higher frequencies, not as much contrastive phonetic information about vowels gets communicated; this is why vowels on high notes are naturally perceived as sounding very close together, even without structural modification.

In vocal pedagogy, there are many methods to shift the amplified resonances (or formants) of the sound by physically altering the length of the vocal tract or moving the articulators. More specifically, there are physical modifications one can perform while singing vowels set very high in the voice to adjust the resonant frequencies of the vocal tract. This can be done with the goal to be heard over an orchestra, increasing vocal stamina, creating a ‘ring’ in the voice, or sounding better in general. For different vowels, singers generally modify the location of the major constriction, the size of the constriction, and the opening of the mouth. The specific methods that I know of range from opening the jaw, creating an embouchure by “smiling” and raising the cheekbones, modifying tongue position, or shifting the head farther back to align with the spine. These modifications can provide a sort of resonance tuning so that the amplified frequencies of the vocal tract align with the pitch. This is perceived with a more even and louder sound at the cost of losing vowel information. This trade-off results in losing even more vowel information than is already inherently lost with the high pitch (wide spacing of harmonics). In this paper, I will compare unmodified vowels to modified vowels and their acoustic correlates. I will investigate the questions: when the singer changes the vocal tract configuration and 'modifies' the vowel, what are the acoustic correlates of these structural modifications? Do the effects of vowel modification and raising pitch manifest differently from vowel to vowel? Furthermore, which factor contributes more to the loss of vowel information: vowel modification or increasing pitch?

2. Methods and Procedure

2.1: Stimuli

For this study, I included six different measures of three vowels /i,a,u/. These are some of the most common vowels in singing, and they offer some degree of variety because they allow me to look at a tense front vowel, a lax back vowel, and a lip-rounded vowel. Each vowel was performed spoken, sung on a low part of my range, a middle part with modifications, a middle part without modifications, a high part with modifications, and a high part without modifications. On the western twelve-tone scale, the low note is middle C, or C4, the middle note is C5, and the high note is C6. The six different measures are as follows for each of the three vowels:

- Spoken
- Sung on C4 (no modification)
- Sung on C5 with modification
- Sung on C5
- Sung on C6 with modification
- Sung on C6

Note: Here, the label of modification means sung with my personal technique, including some of the methods discussed in the introduction that I apply to my own study. Unmodified means that air was pushed through the constriction I would need to make for regular speech to the best of my ability. In this paper, the lack of a modification marker should be taken to mean unmodified.

2.2: Participants

I am using recorded data from one participant, myself. I am a classically trained soprano working towards a career in operatic vocal performance. I am in my eighth year of training.

2.3: Recording Settings

I recorded the sound files in a relatively silent and noise-free room. For the modified recordings, I attempted to sing with the structural adjustments I know of which felt the best to me in my personal technique. Since the goal was to generate natural data, I tried to sing how I normally do and tried not to force any additional modifications on top of that. For the unmodified recordings, it was a bit more difficult; I made the constriction for how I would normally produce the vowel in speech and then forced air through at the higher pitches. As I recorded each vowel, I tried to phonate with the same energy and duration (around 3-4 seconds each) and took breaks in between recordings to make sure each one had similar energy levels. The signal-to-noise ratio was consistently ranging from 50-52.

2.4: Measures used

For analysis, I had two main groups of comparison: between modified and unmodified, and between vowel qualities. For each vowel, I took mean f0 (fundamental frequency) values from the Praat function 'get pitch' and intensity values from 'get intensity'. Then, I looked at spectral analysis by selecting the midpoint on the sound file and taking the measures of the formants F1, F2, F3, and F4 using the Praat function 'formant listing'. I created individual spectra using the Praat function 'spectral slices' for all files. I performed LPC (linear predictive coding) analyses on every one of the six measures for each of the three vowels, as well as the center of gravity. I also recorded the time marking on the point. The quantitative measures I used included:

- Mean f0
- f0 at midpoint
- Timestamp
- F1, F2, F3, F4
- Intensity
- Center of Gravity (COG)

I resampled every sound before taking the LPC analysis. For the high [a] sounds, they had an initial sampling rate of 48000, so I sampled these down to 12000 and used 14 coefficients. For other files, the initial sampling rate was 44100, so I sampled them down to 11025 and used 12 coefficients. After fiddling with the LPC coefficients, I found that these settings yielded the best results for my data. I looked at both narrowband and wideband spectra.

Controlling for vowel quality, I was looking for changes in the measures between the different pitches and between the modes of phonation (modified vs. unmodified). Specifically, I wanted to look for certain energy concentration patterns which may be telling of the distinction between modified and unmodified vowels. I expected the middle voice stimuli to be the most telling of this since it occurs somewhere between completely losing vowel information and completely retaining it. I also looked at each of the six measures between different vowel qualities to see if there were any contrastive cues that sopranos give to hint at vowel quality. I expected that these cues would become less apparent as the pitch raises.

2.5: Expected correlates of vowel modification

Building upon Kent (1993), I looked for the expected acoustic patterns associated with vowel modification, including a phenomenon called F1 raising. According to Kent, for sopranos, the jaw moves open with higher notes when F0 exceeds F1. This is because if the speech-like/lower register constriction is retained, the sound level of the vowel is reduced. Opening the jaw compensates for this and raises the frequency of F1, essentially tuning it to f0. I predicted that in the modified files, I would see a consistent raising of F1 to meet f0 whenever the f0 goes above the range of F1, such as in the highest dataset where I am singing a C6. I looked for F1 raising in both the modified and unmodified files. Since F1 is affected by jaw movement and F2 is affected by tongue movement, I looked for these relationships between the modified and unmodified sounds as well as between vowels.

3. Results

For this section, I will explain my results for each parameter of measurement I took and fixate on both the differences between sound types (modified vs unmodified), as well as between different vowels /a, i, u/.

In terms of general findings, I found that there were contrastive spectral differences between vowels, but these quickly neutralize as the pitch rises. Perceptually, the files recorded on the high C (C6) all sound almost the same. This is because most vowel information is communicated in the 200-2000 Hz range, and at a high C, there can only be one harmonic in this range. Therefore, little to no vowel information is communicated. Furthermore, this effect is exaggerated in the modified vowels. Essentially, when singers modify vowels, we get a much louder and 'resonant' sound at the expense of the listener being able to distinguish between vowels.

<u>3.1: F1 Raising</u>

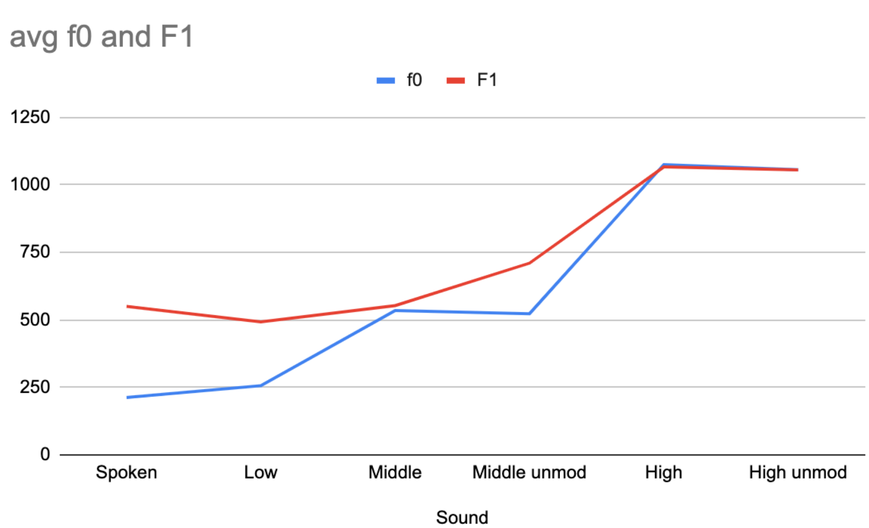


Figure 1: Average f0 and F1 of all vowels vs. sound type

In general, once the f0 gets into the realm of F1, we can see that F1 starts to rise along with f0. In fact, the F1 actually dips below the f0 in the high C6 range in both modified and unmodified files. I was expecting to only find the F1 raising within the modified files, but it was also present in unmodified sounds. Between the unmodified and modified files, there is not a salient difference; since the high unmodified files have a lower F1 than their modified counterparts, while the middle unmodified files show a higher F1 than the modified files. Because of this, it is difficult to identify any significant difference here, especially accounting for the inherent f0 difference between sound types.

Here, the seemingly inherent difference in f0 is something else to note; I was consistently singing under-pitch in the unmodified sounds, perhaps due to a tight speech-like constriction that is unfavorable for singing.

In terms of F1 raising between the various vowels, there were more significant differences, especially involving the [a] vowel. However, the distance between f0 and F1 in all of the spoken and low C4 data was still very similar between vowels.

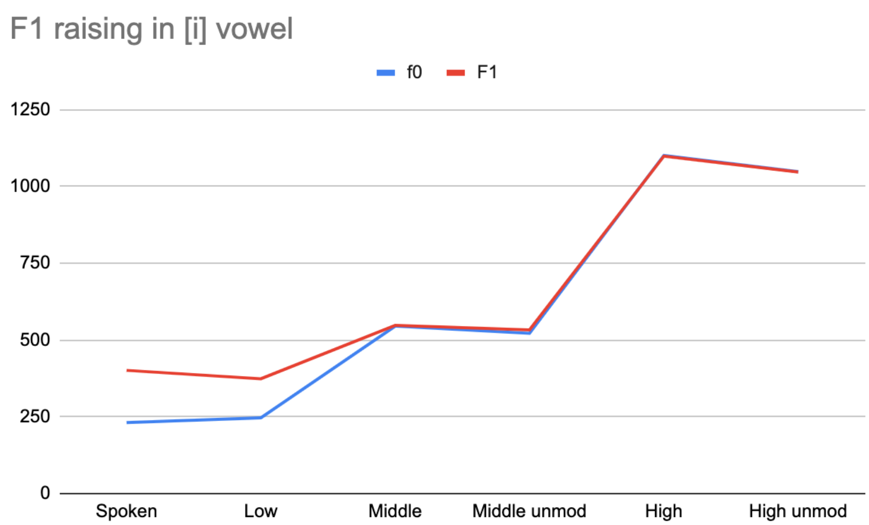


Figure 2: F1 raising in [i] vowel; F1 vs. sound type

Here, we can see that the F1 is almost fleshed with f0 once it enters the C5 range. Once again, we don't see any significant difference between modified and unmodified files.

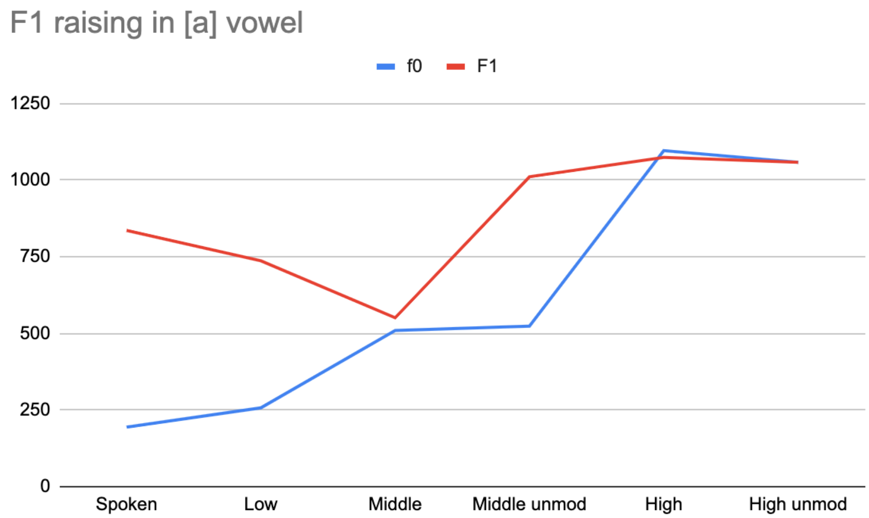


Figure 3: F1 raising in [a] vowel; F1 vs. sound type

When considering the F1 values for each sound type of [a], we can see that the F1 is less close to the f0 values when getting up into the C6 range. There is a considerable gap between f0 and F1 specifically in the middle unmodified files. It also seems as if the F1 dips down toward f0 in the middle modified files. Once again, we see the F1 actually dropping a little below the f0 in the C6 range.

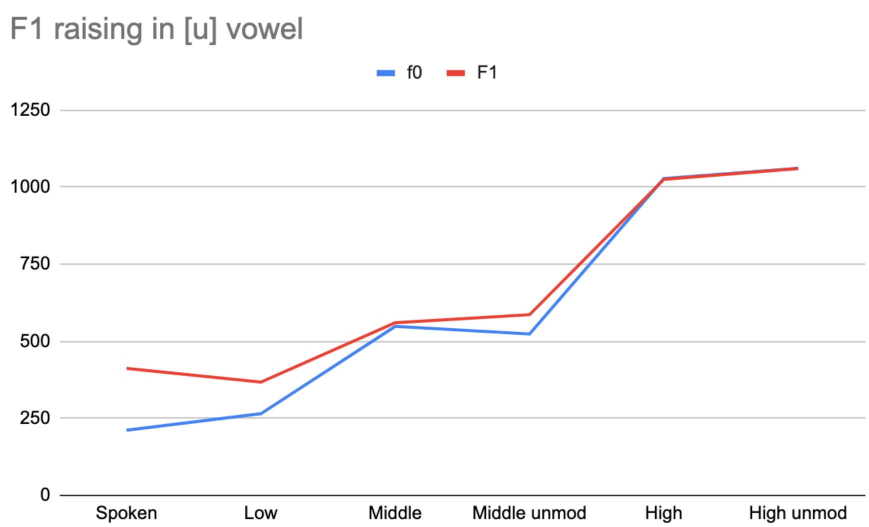


Figure 4: F1 raising in [u] vowel; F1 vs. sound type

With the [u] vowel, there is a considerable amount of F1 raising in the middle and high ranges, but the two lines aren't as fleshed with each other as they are in the [i] vowel.

3.2: Center of Gravity

The Center of Gravity measures how high the frequencies of a certain sound are, on average. If the sound is dominated by higher frequencies, the COG will be higher. In general, when looking at COG between sound types, the modified files have a much lower COG than their unmodified counterparts because they are more dominated by the fundamental frequency.

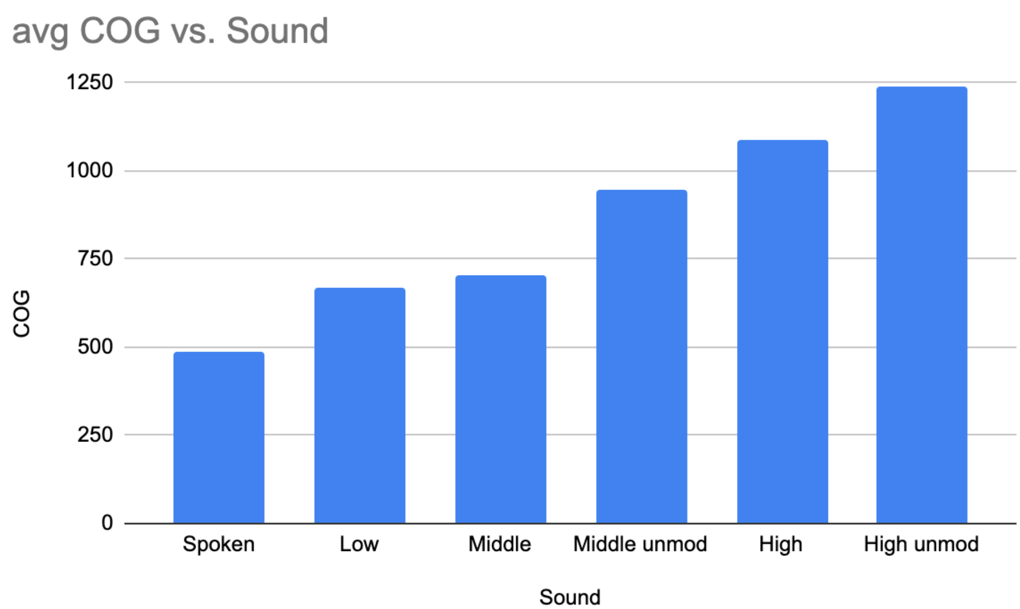


Figure 5: Average Center of Gravity vs. sound type

Even though unmodified and modified files are meant to have the same approximate pitch, the modified files have a consistently lower COG because the signal is dominated by the fundamental frequency, while the unmodified have a higher COG because of the higher overtones and more broadband signal. This difference is visible in the higher frequencies present in the unmodified spectra, presented in Figure 6.

unmodified middle [i] modified middle [i]

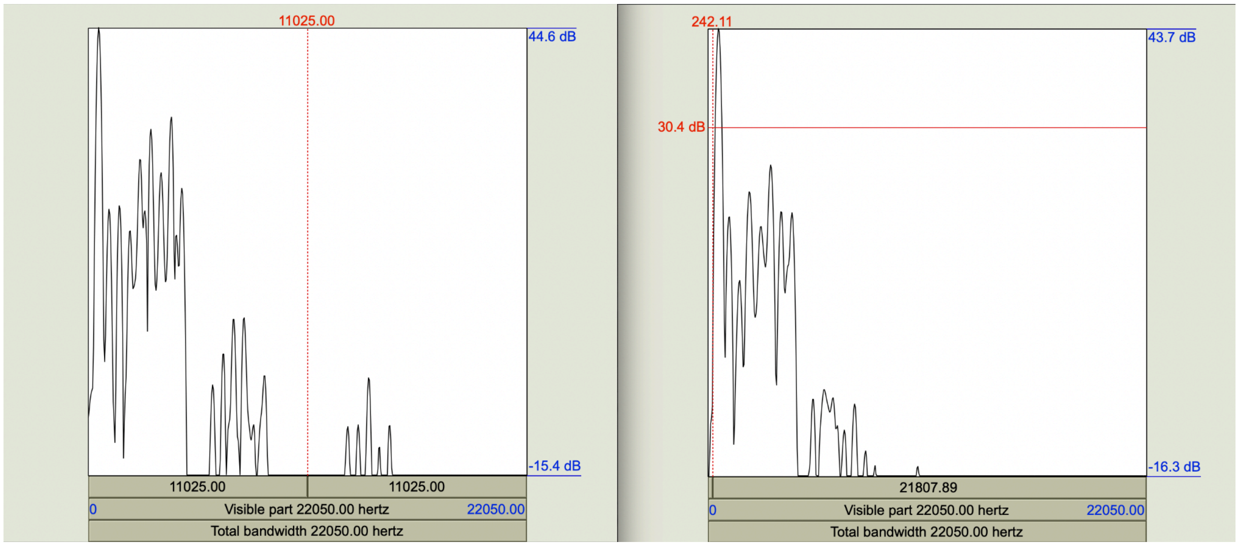


Figure 6: spectra of unmodified [i] vs modified [i]

We can see this in the waveform as well; the modified files look more sinusoidal, while the unmodified signal looks more triangular, indicating higher overtones. Since the unmodified sounds have more broadband signal, the peaks are somewhat triangular in the waveform (and they showed higher energy concentrations in their spectral slices). The waveform shape differences are shown in Figure 7.

unmodified middle [i] modified middle [i]

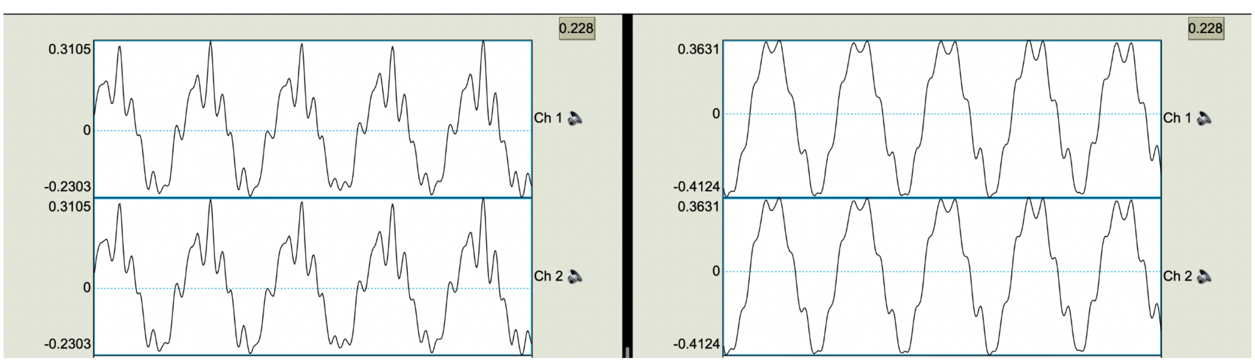


Figure 7: waveform of unmodified [i] vs modified [i]

In terms of the COG differences between vowels, they may be due to the inherent spectral differences between the /a, i, u/ sounds. [i] and [u] have very low COGs when compared to the [a] vowel, especially in the spoken data. Perhaps these inherent differences in where the energy concentrations lie are indicative of differences in the perception of the different vowels.

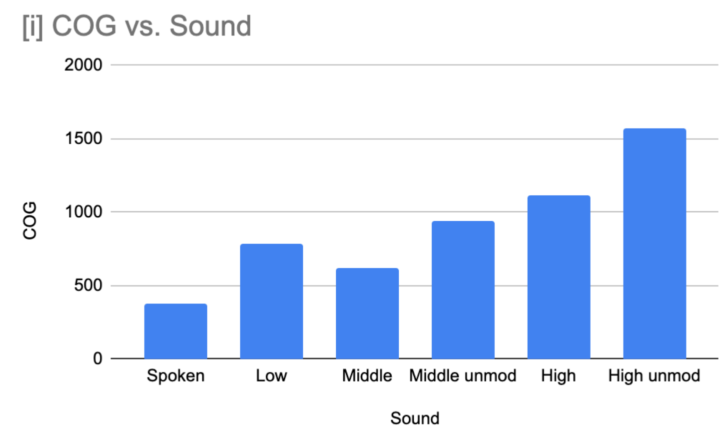


Figure 8: COG in [i] vowel; COG vs. Sound

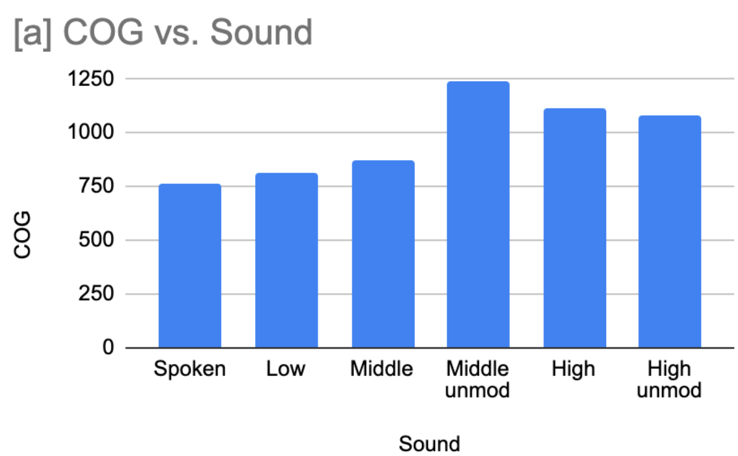


Figure 9: COG in [a] vowel; COG vs Sound

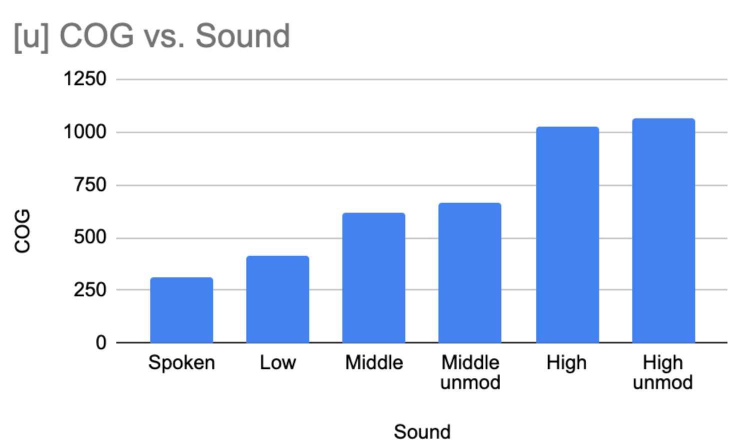


Figure 10: COG in [u] vowel; COG vs. Sound

The observation that the modified sounds have a lower COG than their unmodified counterparts is present in different degrees throughout the different vowels. The difference between modified and unmodified is more pronounced in the [i] vowel and less pronounced in the [u]. The high unmodified sound of [a] is one exception to my observation that the COG for modified sounds is always lower; in this case, it is actually higher than its unmodified counterpart.

3.3: F2 and Vowel Backness

F2 is traditionally associated with tongue position and vowel backness. A high F2 is associated with a front vowel, and a low F2 is associated with a back vowel. The smaller the space of the 'tube' between the front of the mouth and the tongue, the higher the F2. Aggregating the data for all vowels, Figure 11 shows the F2 correlates of the different sound types recorded.

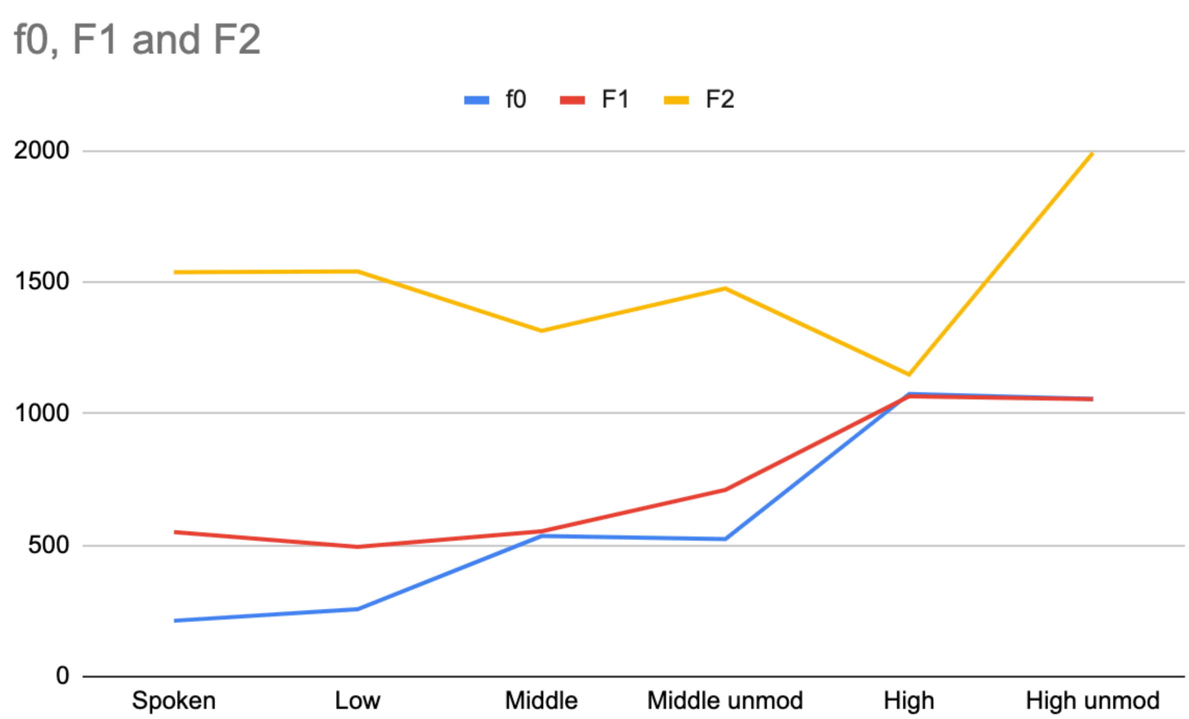


Figure 11: f0, F1, F2 of different sound types

The F2 is always higher for unmodified sounds, meaning the tongue is more in front of the mouth for the speech-like constrictions. This makes sense because modified vowels are associated with opening the constriction to amplify certain resonant frequencies of the vocal tract. For example, when the singer opens their jaw or positions the tongue farther back in the mouth to modify their vowels, the F2 will decrease.

This also has a perceptual correlation; one of the reasons we cannot distinguish between vowels at a high pitch (especially when there is vowel modification) is because of this neutral tongue placement and lowered F2.

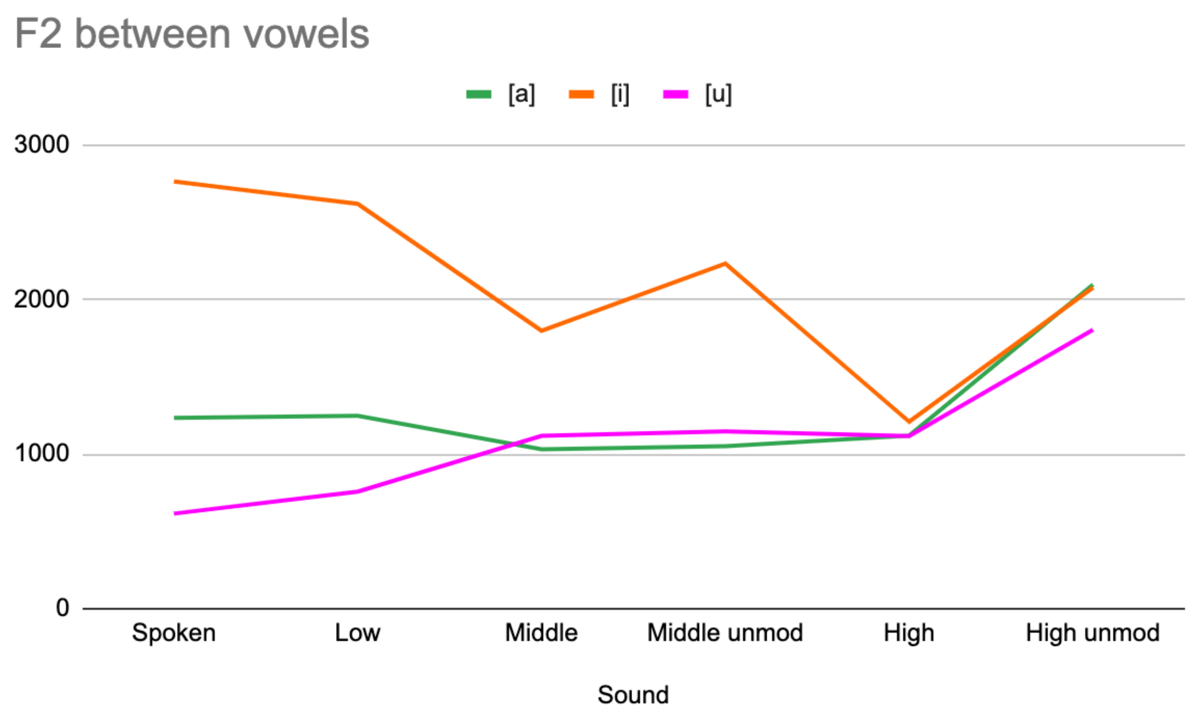


Figure 12: F2 of the vowels [a, i, u] vs. sound types

Between the vowels, there is an interesting phenomenon that is telling of vowel modification; the aggregate line for [i] has the greatest F2 difference from the others because this vowel has the most drastic change in tongue position between modified and unmodified.

It is also important to note that as the vowels move up into the C6 range, the articulatory differences become neutralized, and therefore the F2 lines move closer together. The F2 is higher for [i] because it is a front vowel, but this difference is less pronounced as pitch raises.

When the vowels are modified, they are articulatorily and perceptually more alike, and therefore have similar F2s. Therefore, both vowel modification and pitch raising result in more similar F2s. When there is both vowel modification and high pitch, these values are practically identical between vowels. This can be shown in the [i] vowel; the F2 is the closest to that of the other vowels in the modified segments because the articulators are in a more ideal position for singing (which happens to have the tongue farther back in the mouth).

3.4: LPC Analysis

The following are the results of the LPC analysis. For every sound file, I made an accompanying LPC analysis which showed the interactions of the formants. In general, I found that the LPCs became useless as the sound enters the C6 range. The problem here is that there is no vowel information, or formants, to be identified in higher ranges due to the harmonics being so far apart. As the pitch raises, the LPC identifies just the harmonics as peaks because there is no vowel/formant information present. Adversely, LPC analysis is more useful for speech and sung pitches in the lower ranges because the harmonics are closer together, allowing peaks to be found and formants to be identified, and therefore vowel information to be conveyed. This is demonstrated in Figures 13-16 with the [a] vowel of varying pitches.

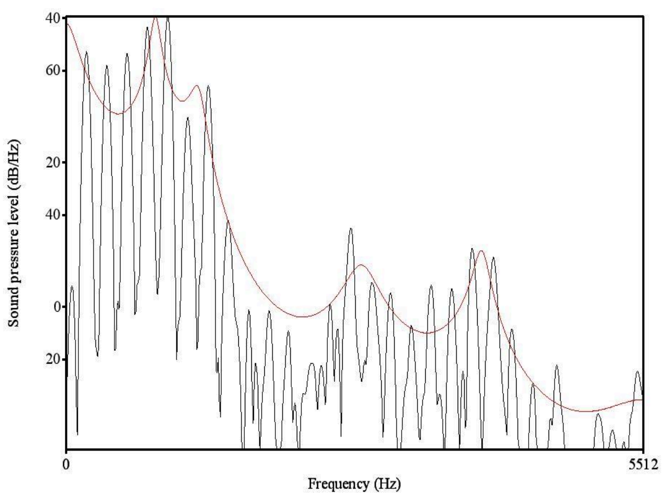


Figure 13: LPC spoken [a]

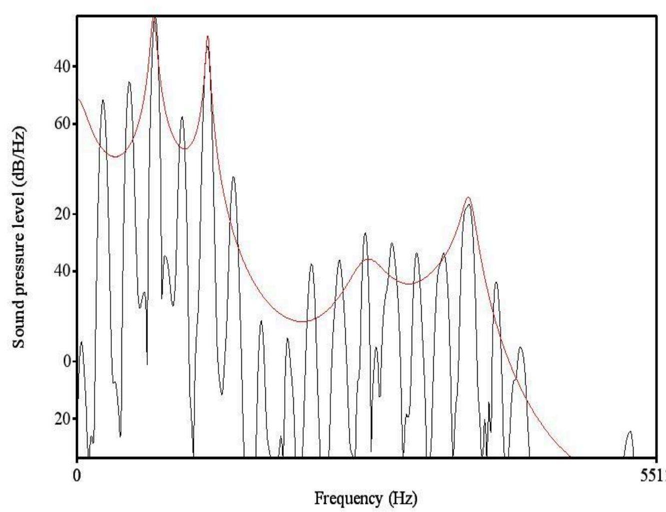


Figure 14: LPC low [a]

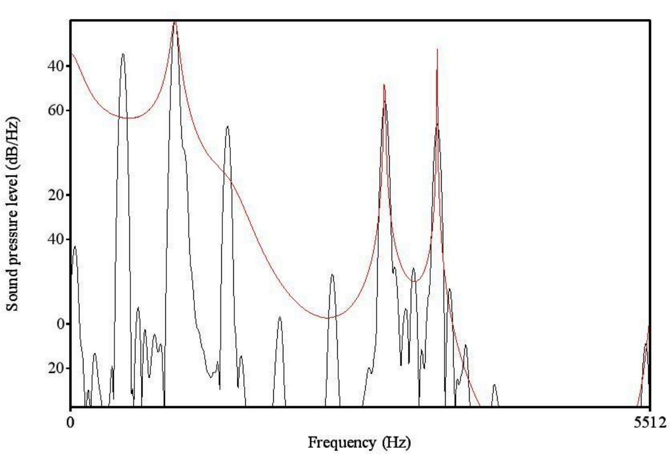


Figure 15: LPC middle [a]

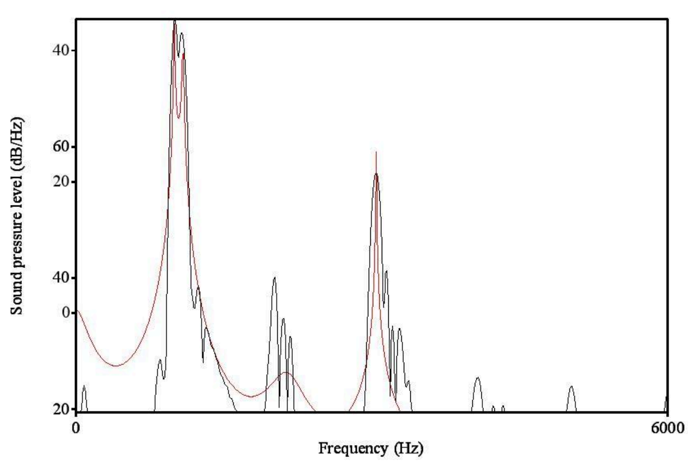


Figure 16: LPC high [a]

This phenomenon can also be shown in the spectra/waveform. Just by looking at the waveform, we can see that the sounds in the lower range have glottal pulses that look much more characteristic of speech, meanwhile, the middle files have less pronounced peaks, and the high files are almost sinusoidal, with no real jagged edges at all.

Low [a] Middle [a] High [a]

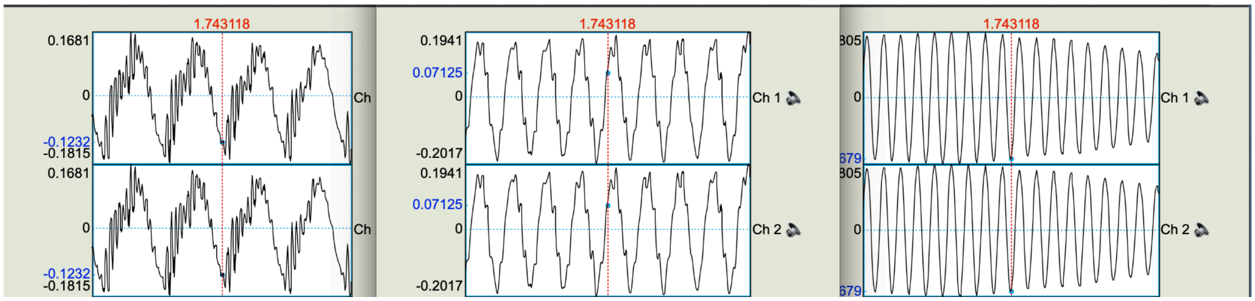


Figure 17: 2:1 Octave relationship in the waveforms of the [a] vowel

What is interesting to see is that since they are three octaves of the same note, we can see this 2:1 relationship between the glottal pulses. Additionally, by extracting the spectral slices, we can see that there are fewer jagged peaks are visible in the spectrum as the note gets higher:

High [a] Middle [a] Low [a]

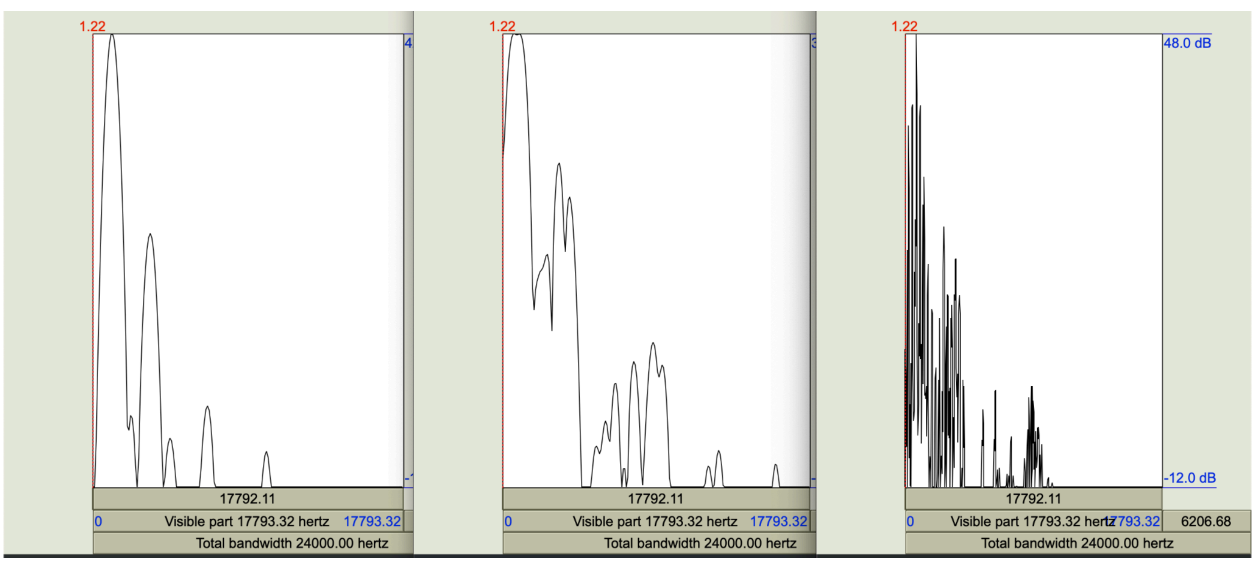


Figure 18: Octave relationship in spectra of the [a] vowel

This phenomenon happens in the LPC spectra as well; the higher the pitch goes, the harder it is for the LPC analysis to find peaks.

Between the modified and unmodified LPCs, we can see once again that the spectra of the modified sounds are more dominated by f0, while the unmodified sounds have higher overtones and more evenly distributed peaks. This supports the earlier findings around COG.

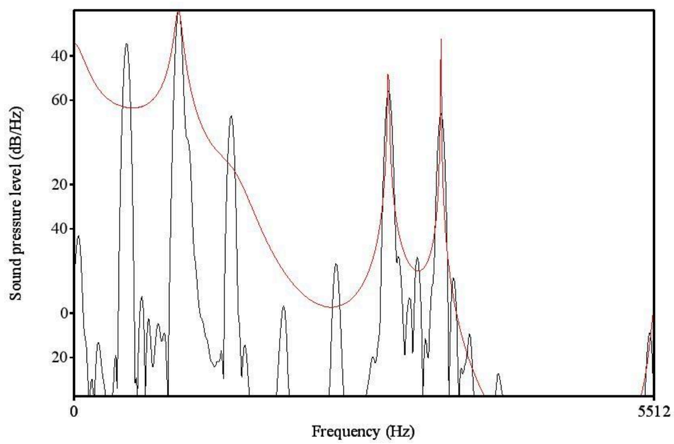


Figure 19: LPC middle [a]

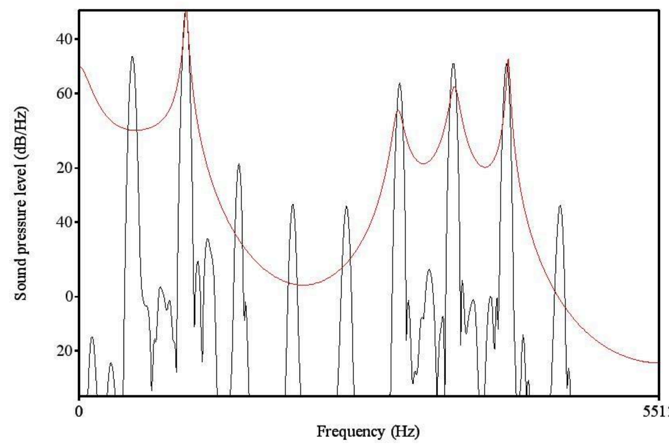


Figure 20: LPC middle [a] unmodified

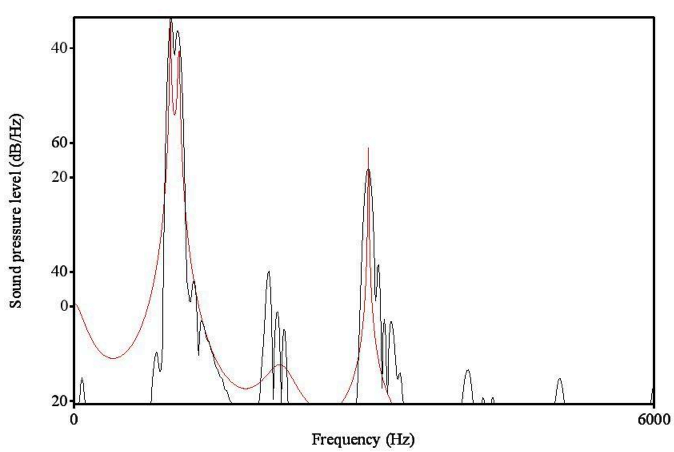


Figure 21: LPC high [a]

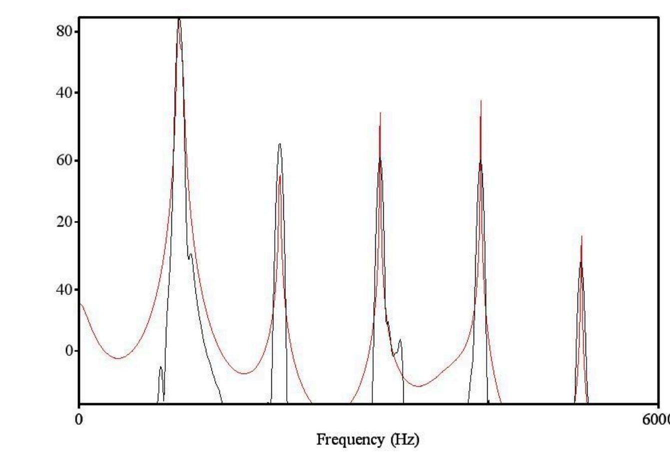
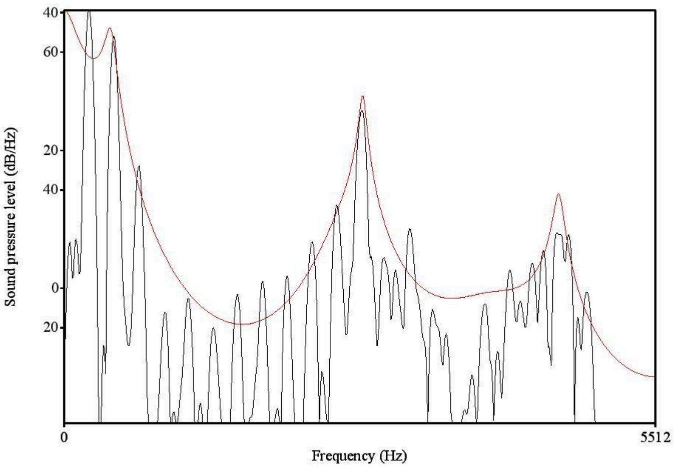


Figure 22: LPC high [a] unmodified

Here, we can see that the peaks of the unmodified files are more evenly distributed across the spectrum, while the modified files have greater concentrations in lower frequencies. This is reflected in the COG findings; the modified files consistently have lower COGs than their unmodified counterparts, across all vowels.

Between vowels, the LPC shows differences in vowel information (formants) in the lower and spoken ranges. However, as the pitch raises, these differences quickly neutralize. For instance, the front vowel [i] has a very far apart F1 and F2, while the back vowel [u] has the F1 and F2 much closer together. We can see this apparent difference in the spoken LPCs in Figures 23-24.



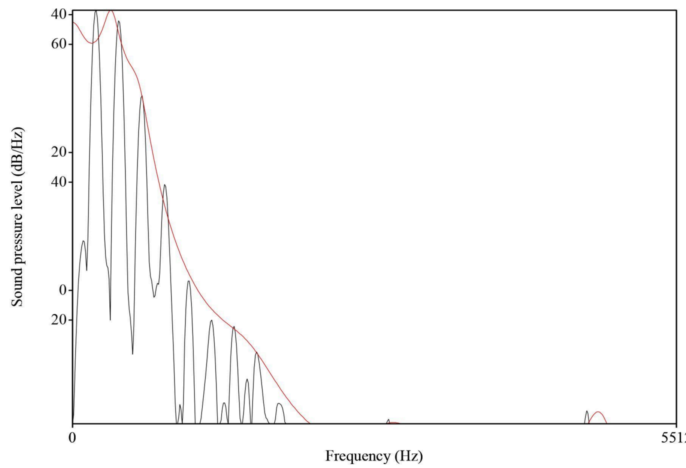
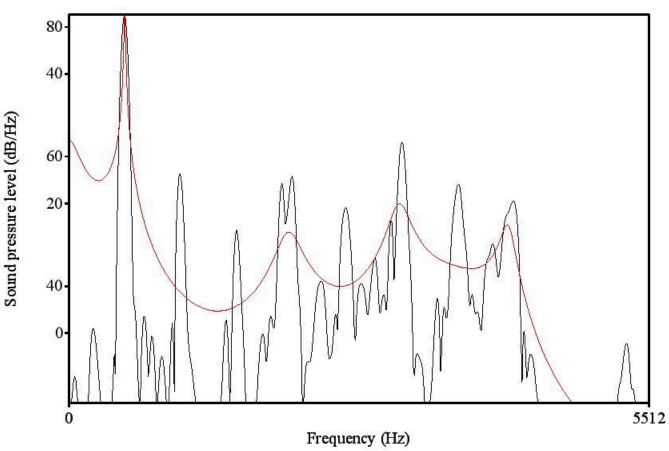


Figure 23: LPC spoken [i]

Figure 24: LPC spoken [u]

The backness of the vowel is reflected clearly by the low F2 in the spoken [u]. However, in the middle and high ranges, these formant differences are neutralized.



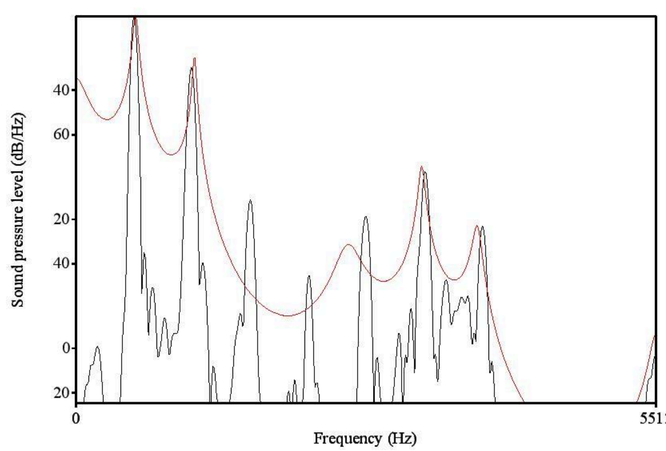
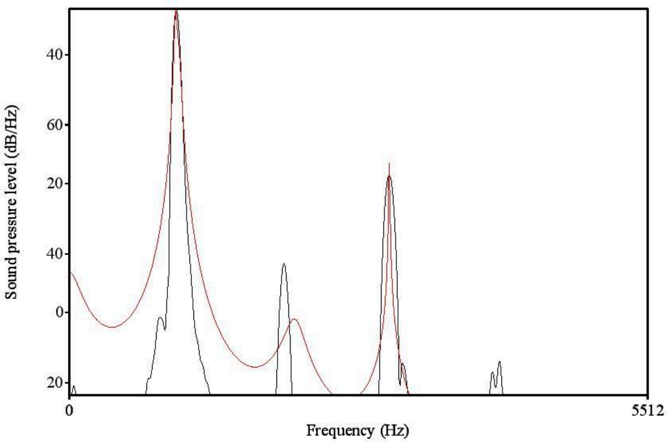


Figure 25: LPC middle [i]

Figure 26: LPC middle [u]

In the middle range, we can still see the wide gap between F1 and F2 in the [i] vowel, vs. the closer together F1 and F2 in the [u]. We can still see some vowel information here, but it is somewhat reduced.



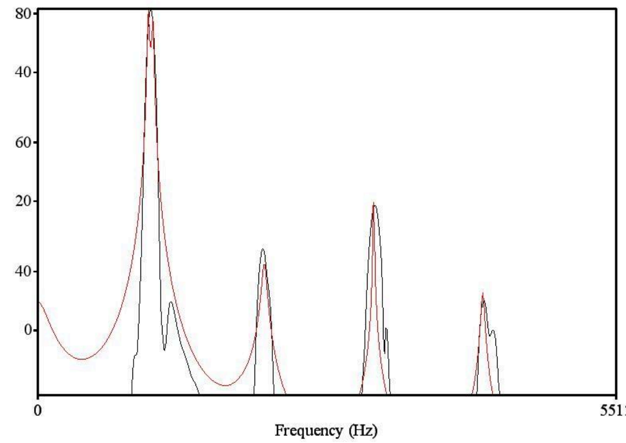


Figure 27: LPC high [i]

Figure 28: LPC high [u]

Here in the high C6 range, almost all of the vowel information is lost; the LPC analysis is not identifying formants, but instead is just approximating the harmonics as peaks. This is because there are no formants to be identified up here as a result of the harmonics being so spaced apart.

In the lower and spoken ranges, all of the vowel information is present for the perceiver to distinguish between qualities. In the middle ranges, the vowels are still distinguishable, but more limited than in the lower ranges. In the higher ranges, there is not enough vowel information for the LPC to identify formants, which corresponds to the quality being unclear in the perception of vowel quality as well.

This is also supported by qualitative observations from the waveforms. Each vowel has its own unique glottal pulse and formant pattern for the low and middle registers, but once they enter the high register, every single vowel looked the same on the waveform, showing this nearly sinusoidal curve. In the waveforms, we can observe how all vowels blend into one, due to a lack of vowel information in higher frequencies. As the pitches get higher, we can see that the differences neutralize between vowels.

From these observations, it is apparent that pitch range has more of an influence on conveying vowel information than structural vocal tract modifications. Both of these factors contribute to distorted vowels in perception, but pitch range is a much more dominant cause of this.

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3.5: Intensity

The intensity in modified sounds was consistently slightly higher than in unmodified sounds.

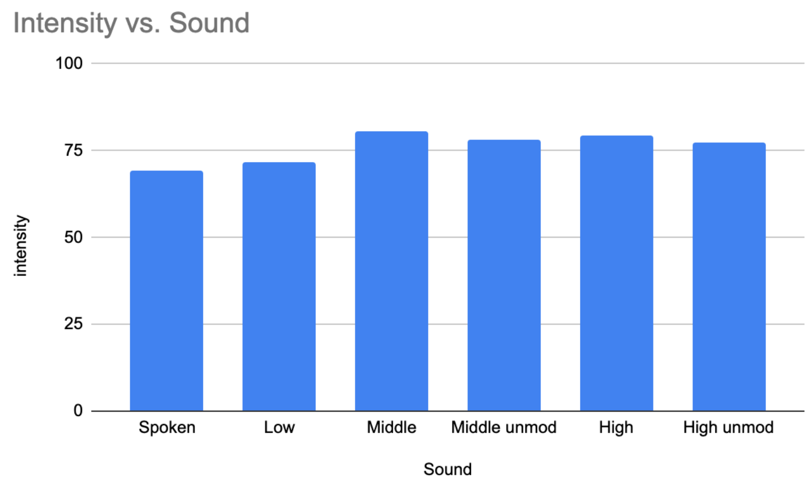

Figure 29: Average intensities for each sound type

This is one result of vowel modification that is favored by singers; higher intensity is a contributing factor to singers modifying their vowels (at the expense of vowel information).

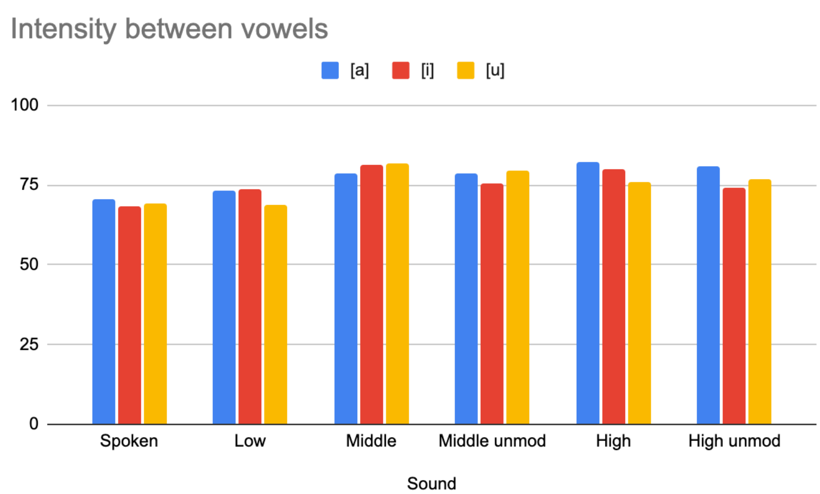

Figure 30: Intensity between vowels [a, i, u]

In terms of intensity between vowels, I found that on average, the intensity of [a] was the highest, followed by [i], and then [u]. However, it is not clear if there is a distinct relationship here, or whether one vowel has an inherently higher intensity than the others.

4. Discussion

From my results, it is apparent that both pitch raising and vowel modification contribute to distorting vowel information. Furthermore, although the effects of modification on vowel clarity are present, the much more influential factor in vowel distortion is increasing frequency. Additionally, the effects of vowel modification and raising pitch manifest differently from vowel to vowel.

Something I did not predict is that vocal tract modification did not have much effect on F1 raising; instead, the dominant factor contributing to F1 raising was pitch. Once the pitch enters the range of F1, F1 can be shown to raise to follow the f0 value. Additionally, it is difficult to say if F1 raising varied from vowel to vowel. However, as the pitch rose, F1 values between vowels got more and more similar, showing this idea of vowel distortion and blending into one neutral vowel.

The f0 was consistently lower in unmodified sounds than in modified sounds. The strained constriction of the unmodified position may have caused me to go flat, or under pitch.

The center of gravity was consistently higher in unmodified sounds. Additionally, the LPCs of unmodified sounds showed more of a concentration in higher frequencies on the spectrum. This is because unmodified sounds have more influences of higher overtones, while the modified sounds are more dominated by the fundamental frequency. COG differences between vowels didn't yield any significant contrastive relationship.

F2 is also consistently higher in unmodified sounds. This makes sense since a high F2 is associated with a front tongue position; the modified F2s are lower because sopranos often position their tongue farther back in the mouth to modify the vowel. This tongue position change is perceived as a more neutral vowel. Between different vowels, [i] has the farthest to move (since it is a front vowel), so this vowel shows the strongest shift in F2 between modified and unmodified. Additionally, in the C6 range, all of the vowels are very similar in F2 across both modified and unmodified sounds. Here, we can see the effects of both modification and rising pitch. This supports the overarching conclusion that the differences between vowels inherently neutralize as the pitch raises. Perceptually, we can observe that both vowel modification and pitch raising result in vowel information being compromised, resulting in a perception of all vowels blending into one neutral vowel. This perception is marked by the acoustic correlates of F2 getting more similar across all vowels as the frequency increases.

This conclusion is also supported by the LPC analysis. Here, the differences between modified and unmodified were present, but the more dramatic differences were between pitches. With the LPC analysis, we can see how vowel information is lost every time the pitch rises, due to there being more widely spaced harmonics. This is the inherent problem with the LPC; in high ranges, there is no vowel information, or formants, for it to identify. Perceptually, this correlates with all vowels blending into one, due to a lack of vowel information. Between vowels in low and spoken ranges, the LPC shows clear vowel information and resonant frequencies, but as we enter the middle and high ranges, these formant differences neutralize.

The intensity in modified sounds was consistently higher than that of unmodified sounds. This makes sense because the vocal tract modifications most favorable for singing are those that amplify certain resonant frequencies and intensify the sound. Increased intensity is one of the favored outcomes of vowel modification that are gained at the cost of vowel information.

One takeaway is that although there are clear acoustic differences between modified and unmodified vowels, a rising frequency much more heavily contributes to vowel distortion. Any contrastive differences between vowels are neutralized as frequency rises. This is because different pitch levels, especially higher ones, are inherently and physically limited as to how much vowel information they can convey. Additionally, at the cost of even more vowel information, a singer can choose to modify their vowels at these high pitches to increase the intensity of the sound and become more resonant. Intensity, COG, f0 and F2 all showed clear differences between modified and unmodified sounds.

5. Limitations

Due to limited data, it is difficult to extrapolate my results to all sopranos. This is especially true since different trained singers use various vocal techniques, of which I am just representing my own. If I were to redo this exact study, I would record everything without vibrato because it may have messed with the f0 measurements. If I were to expand on this study, it would be interesting to compare untrained vs. trained singers and compare modified and unmodified vowels that way. Another idea I had that could build on this study is to find out exactly when F1 raising kicks in. For this, I would involve more participants and record each of them singing an ascending scale connecting their low and middle ranges. This way, I would have more than three pitches to go off of to find the exact note where f0 enters the range of F1 for each participant.

6. Conclusions

Pitch has more of an influence on conveying vowel information than structural vocal tract modifications. Both of these factors result in perceptually distorted vowels, but pitch is a much more dominant cause of this. It is also important to note that singing higher pitches anatomically lends itself to vowel modification; you may be doing it without even realizing it. In this way, vowel distortion from raising the pitch and from vocal tract modification seem to go hand in hand. For example, it was unnatural for me to produce a tense constriction for the [i] unmodified vowel, because it is just easier to sing with an open mouth and a lax tongue position. Because of this relationship the two factors have with each other, these results surrounding how rising pitch affects vowel information would be salient even without the unmodified vs. modified comparison.

Therefore, I can summarize my findings into three statements:

1. Spectral differences encoding vowel information neutralize as the pitch rises due to inherent acoustic properties like increased harmonic spacing.
2. Vowel modification is also a contributor to lost vowel information; these differences between unmodified and modified vowels are apparent in F2, intensity, and COG.
3. Pitch raising is a more dominant influence on the loss of vowel information than vocal tract modification, but usually these two factors work in tandem.

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