Mobile Apps and Biofeedback in Voice Pedagogy

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ADVANCEMENTS IN MOBILE TECHNOLOGY have revolutionized nearly every sector of our lives. We connect with friends, count steps, meditate, purchase movie tickets, and order Thai food. Like a virtual fingerprint of our individual preferences, the seemingly endless array of mobile apps can define and enhance our interests. Music applications are a large part of this industry, and new generations of singers use mobile devices to listen to songs, record lessons, read, and annotate scores. Analysis and recording applications geared toward advanced musicians include acoustic visualization, involving various forms of spectrograms.

However, spectrographic technology used by voice scientists and pedagogues has not fully crossed over into the mainstream population of students and teachers. One reason for the lack of pedagogic use is that acoustic computer software has been geared primarily toward research- and academic-oriented pursuits. Acoustic software can be complicated to learn and tedious to analyze. In addition, the traditional teacher/student paradigm, proven successful for centuries, is a very effective way of teaching voice; as a result, there can be resistance to introduce new forms of pedagogic analysis in an already well functioning studio.

The integration of technology for targeted purposes can aid both student and teacher in many important ways. In most instances it leads to increased accuracy in a shorter amount of time. It also allows students to self-check particular directives in their own individual practice. Identifying beneficial areas of biofeedback is critical in determining where these tools can have maximum effectiveness. All voice teachers, students, singers, and scientists share the same goal: to lead singers in the most healthful and aesthetically pleasing way to find their authentic voice. The bigger the toolbox, the more resources we have to achieve these goals. Teachers will always be invaluable, irreplaceable, and necessary, but the process can, and should, evolve.

THE ROLE OF BIOFEEDBACK

Biofeedback is a scientifically proven process, and, given its "mind to motor" coordination requirements, singing is an ideal human action for the implementation of this effective tool. Technological displays of visual feedback in rehabilitation medicine have facilitated normal movement patterns after injury for more than fifty years.[1] In these cases, a measured variable (e.g., involuntary, such as heart rate; or voluntary, such as limb movement) is

transformed into a display. Using visual feedback, the patient can regulate output toward improvement. The sports medicine field has implemented a visual biofeedback protocol called Real-time Optimized Biofeedback Utilizing Sport Techniques (ROBUST) for both injury prevention and training.[2] Otolaryngologists also have used biofeedback for dysphagia.[3] For these swallowing disorders, visual biofeedback has proved to be the most efficacious tool over any other feedback method, including verbal directives from the physician.[3] This has some obvious and fascinating correlations to the singing paradigm in which the main corrective element is verbal feedback from the voice teacher. In each of these examples, the addition of visual biofeedback dramatically enhances recovery and improvement. The neuroscience behind these results is complex and a topic that researchers continue to pursue. But in simple terms, the brain is simply redirecting its own robust feedback processes via a different input. In addition, the remarkable plasticity of the brain allows new neural networks to form, correcting signals and creating new outputs. Models of feedback learning indicate that the criteria necessary for success both neurologically and psychologically are: (1) perceptibility, the subject can perceive the biosignal; (2) autonomy, the subject can self-regulate the output; (3) mastery, the subject can exert control over the biosignal; (4) motivation, the subject is satisfied by the outcome; and (5) learnability, the biofeedback enhances the subject's learning.[4] These properties dictate the success of biofeedback protocols and are clearly applicable to many aspects of singing.

Recently, motor learning principles have been integrated into mainstream voice pedagogy.[5] However, singing is one of the most unusual and complex motor activities, involving the coordination of more than one hundred muscles and broadly connected brain regions to coalesce into a single vocal output. Thus, such principles must be applied judiciously, and integrating visual biofeedback serves as a bonus anchor for solidifying complex motor processes by enhancing both the speed and quality of targeted motor coordination.[6]

Another benefit of visual biofeedback is that the presence of an additional sensory experience enhances memory and solidifies the positive action in greater detail. Adding a visual association allows the will to be coupled to a new cognitive learning skill, allowing differ-

ent aspects of the brain to converge on a single problem efficiently. There is extensive evidence that multisensory approaches enhance learning, and with the added visual input, motor responses can be both more refined and more integrated.[7]

IDENTIFYING SPECTROGRAPHIC MOBILE APPS

In order to have an effective biofeedback mechanism for singing, visualization is of utmost importance. The revolution of mobile apps has yielded a plethora of spectrographic programs available for download, but for their use in voice pedagogy there are some critical parameters:

- simplicity, accessibility, and ease of use for both students and teachers;
- clear and understandable visual display;
- reliable sound input across varied pitches and loudness;
- free or inexpensive; and
- direct pedagogic utility.

To this end, I tested numerous spectrographic mobile apps for their efficacy in satisfying the categories listed above (Table 1). It should be noted that application development is occurring at record pace, and new applications continue to enter the marketplace. Existing applications also continue to evolve via updates and additions. Additionally, applications are not universally available, that is, there are those that can be purchased only in the U.K. and not the U.S., and vice-versa. The following mobile app data merely give a snapshot in time of what existed between the years 2016–2018 when actively testing for this project; the pedagogic impact, however, is applicable to any useful spectrographic application, and my hope is that regardless of the software, the ideas will be helpful across technologies. I will continue to test applications and will make all of the information accessible to the community.

In the ensuing discussion, I will present data from the best of four mobile apps that exhibited the greatest utility, with primary focus on the most efficacious biofeedback applications.

PitchLab by Karl Morton is a free guitar tuning iOS application (Figure 1). The spectrogram component is an additional download for ninety-nine cents and

TABLE 1. Summary of Top 8 Spectrographic Mobile Applications for Voice Pedagogy. *

Top 4 applications mentioned in this paper

	PitchLab *Karl Morton*	SingScope *Springwell*	AudioAnalyzer *Pawel Krzywolzinski*	SpectrogramPro *Dominik Seibold*	SpectrumView *Oxford Wave Research*	Finger Voice *wavepixs*	Live Spectrogram *Krueger*	Spectro-Real *Wevosys Franke*
Cost	Free	Free	$19.99	$3.99	Free	Free	$1.99	Free
Fundamental only	YES (99 cent in-app purchase)	YES	NO	NO	NO	NO	NO	NO
Linear Spectrograph	NO	NO	YES	YES	YES	NO	NO	NO
Log Spectrograph	NO	NO	YES	YES	YES ($1.99 in-app purchase)	YES	YES	YES
Db and/or waveform	NO	Waveform	YES	NO	NO	NO	NO	NO
FFT and/or Spectrum	NO	NO	YES	YES Bode Plot	YES	NO	NO	NO
Real-time	YES	YES	YES	YES	YES	NO	YES	YES
Record/Play Back	NO	YES	YES	NO	YES	YES ($9.99 in-app purchase)	NO	NO
Touch Screen	NO	NO	YES	NO	YES ($1.99 in-app purchase)	NO	NO	NO
Display Quality	+++	++	++++	++	++	+ (small)	++	+++
Ease of Use	+++	+++	+++	++	++	+++	++	++
Gains Adjustment	NO	YES	YES	YES	YES	YES ($9.99 in-app purchase)	NO	NO
Overall Rating	++++ BIOFEEDBACK	+++ Not as sensitive	++++	+++	++	+	++	++

*Table created in July, 2019 at the time of submission. Application availability and cost subject to change over time.

displays a linear representation of the fundamental only. The pros of this app are its clarity and colors that yield an added visual dimension for biofeedback. This feature is the primary reason the application usurps others in its biofeedback effectiveness: the singer has an additional element to associate with frequency. It also has an unusual sound sensitivity, allowing clear, uninterrupted signal for the display. However, as the window captures only three-second samples, one must retain data via screen shots, making it challenging to review and analyze processes or collect data. In addition, the note names have trouble adjusting to non-guitar ranges. The pitches are correct, but the octave numbers can be off (i.e., F_3 shows as F_0). There are also rare occasions where intense shadow overtones appear on the screen. But for most purposes, these elements do not interfere with the biofeedback objective. This application is best used in real time actions whereby the singer responds to the visual cues and implements corrections as they sing.

Singscope by Springwell LLC is another application that offers a linear/fundamental only display (Figure 2). It is an excellent choice if data collection or playback is desired, as the student can hear and see immediately following an exercise. However, both the sensitivity of the input (signal breaks) and the lack of color references for pitch matching make this application less useful for certain biofeedback applications like legato. However, many students have preferred this application for their home practice, given the recording/playback features, while using PitchLab in the studio for more detailed biofeedback.

Audio Analyzer by Pawel Krzywdzinski is a full spectrographic application with more complex feedback and analysis capabilities (Figure 3). At the time of this writ-

ing there is a free version and a pro version with more robust data analysis options for under twenty dollars. Pedagogically, it can be used for biofeedback, but it has greater utility as acoustic clarification and serves as a great introduction for students and teachers who want to become more familiar with acoustic pedagogy and the visualization of sound. Audio Analyzer has excellent input controls to adjust for any volume, and one can choose from multiple display options: linear or log spectrogram analyzer, spectrum analyzer, oscilloscope (full FFT), octave RTA analyzer, and a decibel meter. This application is the easiest to use of all the complex spectrographic applications given its touch screen technology. For more advanced users, a mere tap on a given point and a grid appears, calculating a local measurement of frequency, time, and sound pressure level.

Spectrogram Pro by Dominik Seibold has elements of Audio Analyzer Pro at a lower price (Figure 4). This application works well for most spectrographic needs but the red/orange display is a bit bold for some. The lack of touch screen capability and record/play back option makes it a less favorable application, but many students favor it for the cost advantage.
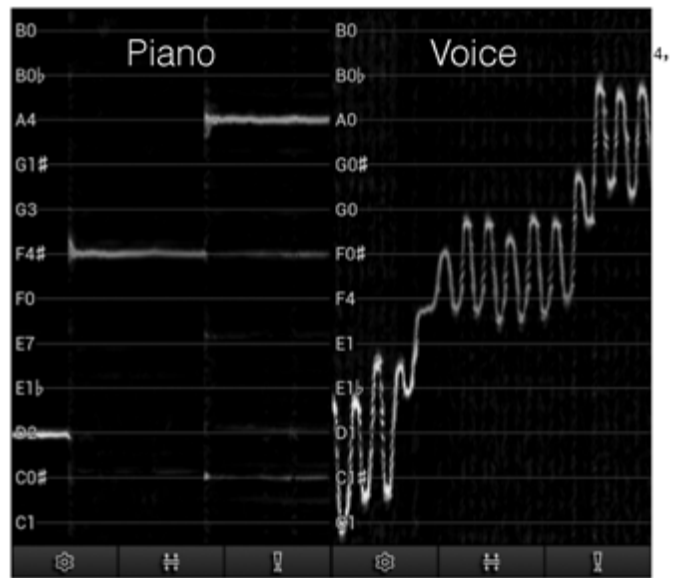

Figure 1. SAMPLE VIEWS of *Pitch Lab* mobile application by Karl Morton. The display is the Pitch Spectrogram add-on showing a linear view of the color-coded fundamental only with samples of piano and voice for comparison. Window limited to approximately three seconds of streaming sound.
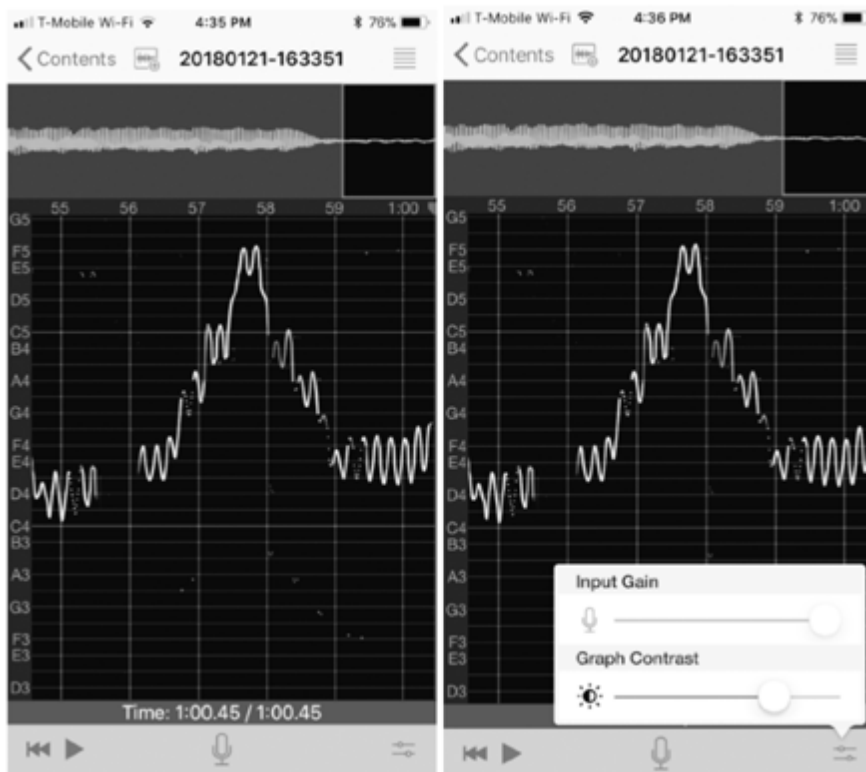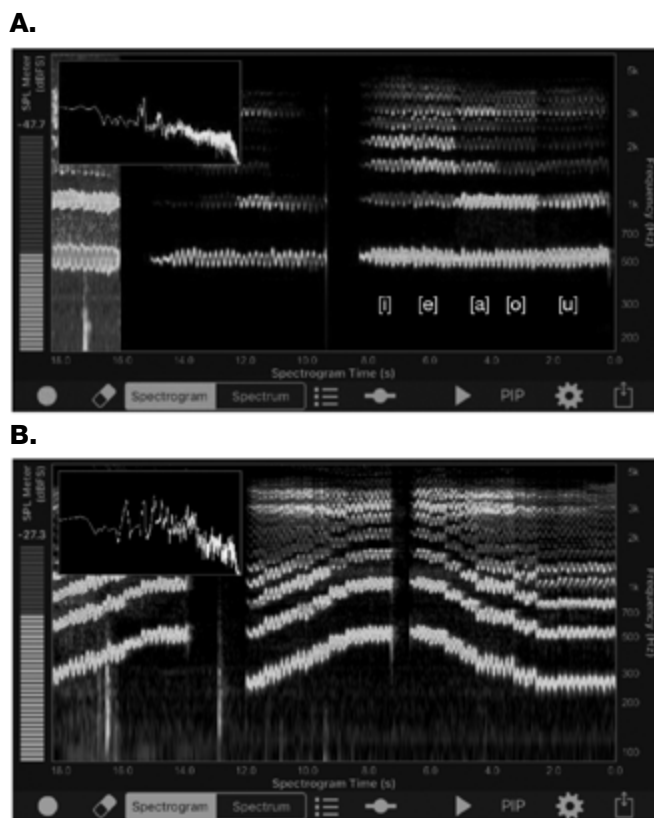

Figure 2. SAMPLE VIEWS of *SingScope* mobile application by Springwell. The display shows a D major arpeggio sung legato by a professional soprano. Note the gains are set at maximum and there are gaps in the graph profile. Also, there are no color differentiation of pitches. However, data can be recorded and played back if desired.

A.

B.

Figure 3. SAMPLE VIEWS of *Audio Analyzer* by Pawel Krzywdzinski
A. Sample voice recording of the vowels [i] [e] [a] [o] [u] on C₅. Settings are spectrogram with spectrum PIP, 18sec sample. Input calculated to reduce background using the Spectrogram Minimum level (dB) sliding bar and screen-zoomed using touch screen expansion to best fit harmonics profile.
B. Sample voice recording of a 5-tone major scale on D₄ on [a]. Settings are spectrogram with spectrum PIP, 18sec sample. Input calculated to reduce background using the Spectrogram Minimum level (dB) sliding bar and screen-zoomed using touch screen expansion to best fit harmonics profile.

In addition to the successful programs, it is also worth pointing out some of the applications that ranked low on the scale of pedagogic utility.

Sing with the Best! appeared promising, given its appealing display that included a streaming log spectrograph and pitch view. It also included a record/playback feature. However, the developer strangely included an analysis element that would give comments such as "pleasing," "slow wobble," and "wide wobble," that selected against any sort of vibrant classical singing.

A.

B.
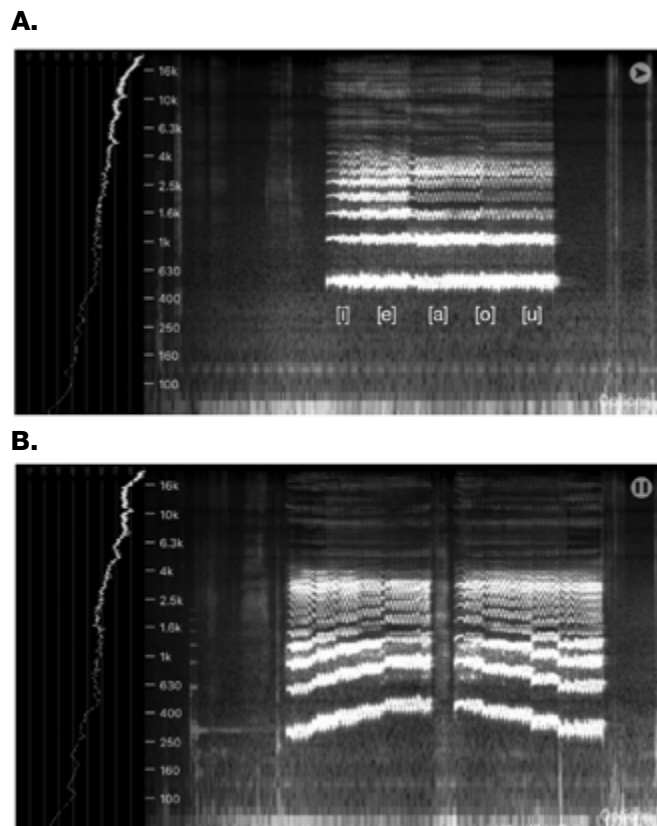
Figure 4. SAMPLE VIEWS of *Spectrogram Pro* by Dominik Seibold.
A. A sample voice recording of the vowels [i] [e] [a] [o] [u] on C₅. Settings are default 24 sec sample with both log spectrograph and bode plot.
B. A sample voice recording of a 5-tone major scale on D₄ on [a]. Settings are default 24 sec sample with both log spectrograph and bode plot.

Perhaps one could use it if they ignored these comments, but in my opinion, criticism like this has no place in a singing application.

Formant Analyzer was unique in that its only display plotted F_1 against F_2 to chart vowel identities. However, in repeated tests, accurate vowel assessments were incorrect over 50% of the time. My conclusion, like for Sing with the Best!, is that these applications were designed with nonclassical voices in mind. The vibrancy element perhaps negatively impacts the algorithms used to analyze the acoustic inputs.

Spectrogram by Schwamb did not include any gain controls at the time of testing, and most classical singing

was too loud for any accurate analysis. Perhaps an external microphone that could be appropriately calibrated would alleviate this challenge, but my goal was to find stand-alone applications that could work with the built-in microphone, thus having the broadest accessibility for students and teachers. It also was priced a bit higher than some of the other applications.

PEDAGOGIC QUESTIONS

The most critical element in introducing this technology is to identify relevant pedagogic questions that easily can be solved via visual biofeedback. Ideally, these approaches would supplement traditional methods (i.e., teacher/student; auditory/kinesthetic feedback), but allow progress to happen faster and enhance understanding of processes.

Simple vocal elements had the greatest success in trials: pitch stability, onset/offset, vibrato, legato, and trills. All of these issues are frequently seen in the studio and have varied traditional approaches for correction. Through use in my studio with students of all ages and abilities, the inclusion of visual biofeedback allowed for real time improvements of specific targets in the majority of singers without any teacher intervention. These data are purely anecdotal: more detailed research is necessary to identify the precise efficacy (this project was mostly unfunded and a labor of love), but the results clearly demonstrate the value of biofeedback for specific pedagogic aims and certainly point to an interesting area for future scientific exploration.

PITCH STABILITY

A multitude of causes can lead to various pitch inaccuracies. Often, when left unresolved, singers can become self-conscious of being too flat or too sharp that they begin to question their ears or mental conception of pitch. The teacher, choir director, or coach can similarly ask students to "think higher" or "listen carefully" when the issue is simply a motor coordination problem, feedback, or other event, and has nothing to do with how they are hearing or how their brain is processing pitch. Alternatively, the focus can be on other specific downstream (i.e., motor output) events like onset, breath, fold tension, tongue, etc. that are independently contributing but do not get at the holistic pitch stability process. This can result in a psychological trap where the singer then overcorrects, doubts, and questions particular pitches, leading to more tension and frustration.

A simple Google search shows how many exercises are promoted to address this singular problem. Yet there has been little mention of utilizing visual biofeedback to aid a singer through this challenge. Figure 5 illustrates two examples of real time biofeedback using the PitchLab application (linear display of fundamental only) resulting in resolved pitch stability in the absence of any other directives: a young, beginner female struggling to sustain a B_3 and an advanced classical soprano whose vibrato was consistently below pitch. In each case, the singer was simply presented with the visual and asked to observe the tone to match the pitch. The process in each case took less than a minute, and usually happens within seconds.

It should be noted that the biofeedback of pitch had an added benefit of stabilizing the tone quality as well, as evidenced by the vibration rates in each image.

ONSET/RELEASE

Generally, how we start a phrase and how we end a phrase dictates the success of a phrase. In reductionist terms, this also applies to a single tone; hence, many singers practice onsets and release with due diligence. The first chapter in Richard Miller's *The Structure of Singing* focuses entirely on this topic, eloquently elucidating approaches and exercises to achieve the balanced onset/release.[8] Alternatively, some genres call for different approaches: for example, starting a phrase with a slide or a glottal. Being able to describe and kinesthetically reproduce what is required can be challenging given the subtitles of coordination required. Adding visual biofeedback to this event can solidify the objective of a balanced onset/release as well as show alternative musical gestures associated with the onset/release.

There are several examples of onset challenges by a range of singers and abilities (Figure 6A-D). These are extreme phenotypes, but the subtitles and comparisons to a well balanced onset become clear with practice. Ideally, the images are coupled with recordings so that apt comparisons can be made and pedagogic corrections are apparent.

Some singers have more issues with the release (Figure 6E). Similarly, visual biofeedback creates another
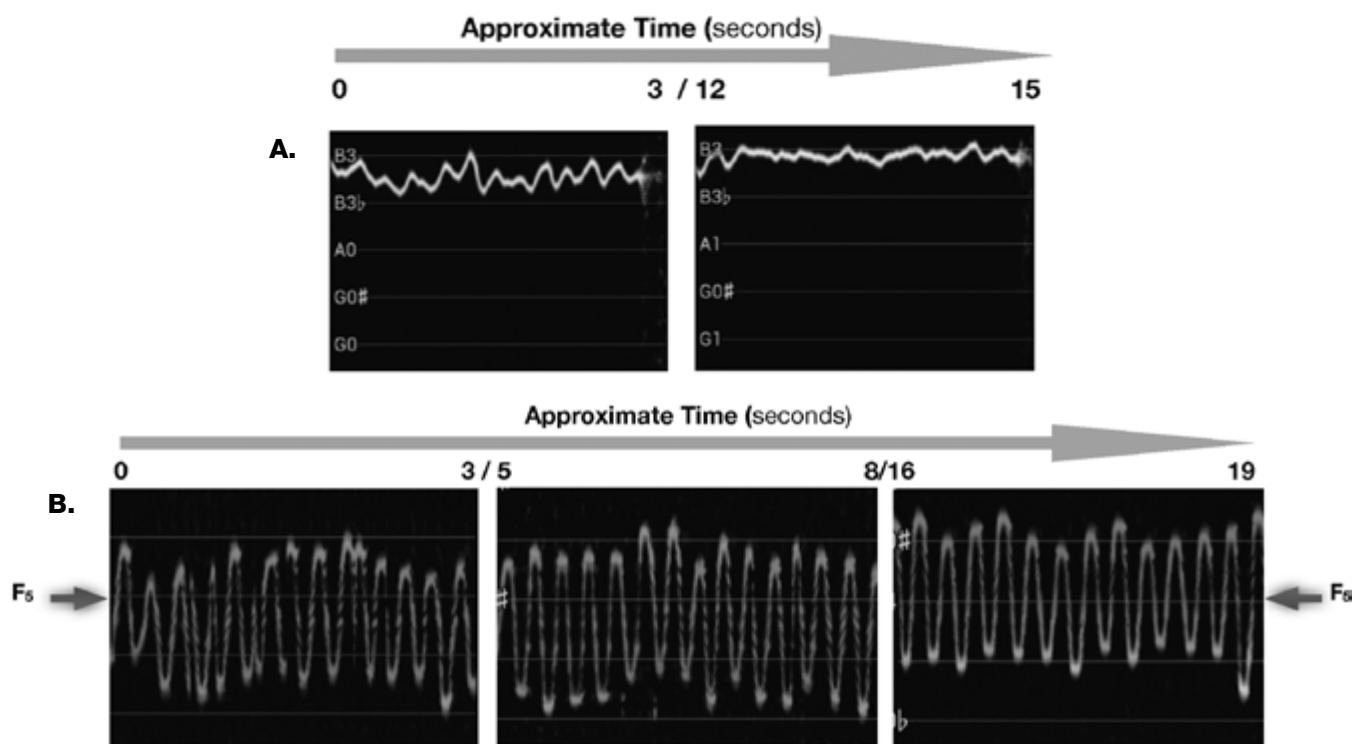
Figure 5. PITCH STABILITY using *PitchLab*.

A. A 13 year old female stabilizes B_3 in real time using visual biofeedback only. Sound is not necessarily continuous and breaths not represented nor indicated.

B. A semiprofessional soprano using visual biofeedback to center vibrato around F_5. Sounds are not necessarily continuous and breaths not represented nor indicated.

point of reference toward awareness and problem solving in conjunction with other methods.

The visual for a well balanced onset in classical singing shows a clear start at the center of pitch, immediate vibrancy, and release on the center of the pitch (Figure 6F). This is also a great tool for students to verify on their own in the practice room: many students improve their onset and release faster than traditional methods using visual feedback between lessons.

VIBRATO

Vibrancy is a classical singing aesthetic indicative of well balanced vocal production. It can be a challenge for some, especially as young singers grow, to find a free, vibrant sound. In addition, stability and rate in advanced singers also may need refinement. In principle, elements of healthy vocal technique are gateways to vibrancy, that is, breath efficiency, fold connection, freedom from unnecessary tension, etc. However, the exact mechanism to produce efficient vibrancy can be challenging to micromanage; teacher directives and kinesthetic awareness are often based on cumulative vocal freedom and timbre awareness rather than specific actions to create vibrancy. In these cases, visual biofeedback can supplement this process in immeasurable ways. Figure 7A-C shows examples of one young singer's journey over two years to find her vibrato after years of straight tone choral singing, using a combination of technique and visual biofeedback. A second example is an adult amateur who was able to correct vibrancy in real time to a generate a more stable sound (Figure 7D). The final example is an older amateur tenor, who claimed to have never sensed his own vibrato, using feedback to gain understanding and stability in his vibrancy (Figure 7E). Note the amplitude and oscillation rate variations that reflect natural vibrato differences between singers.
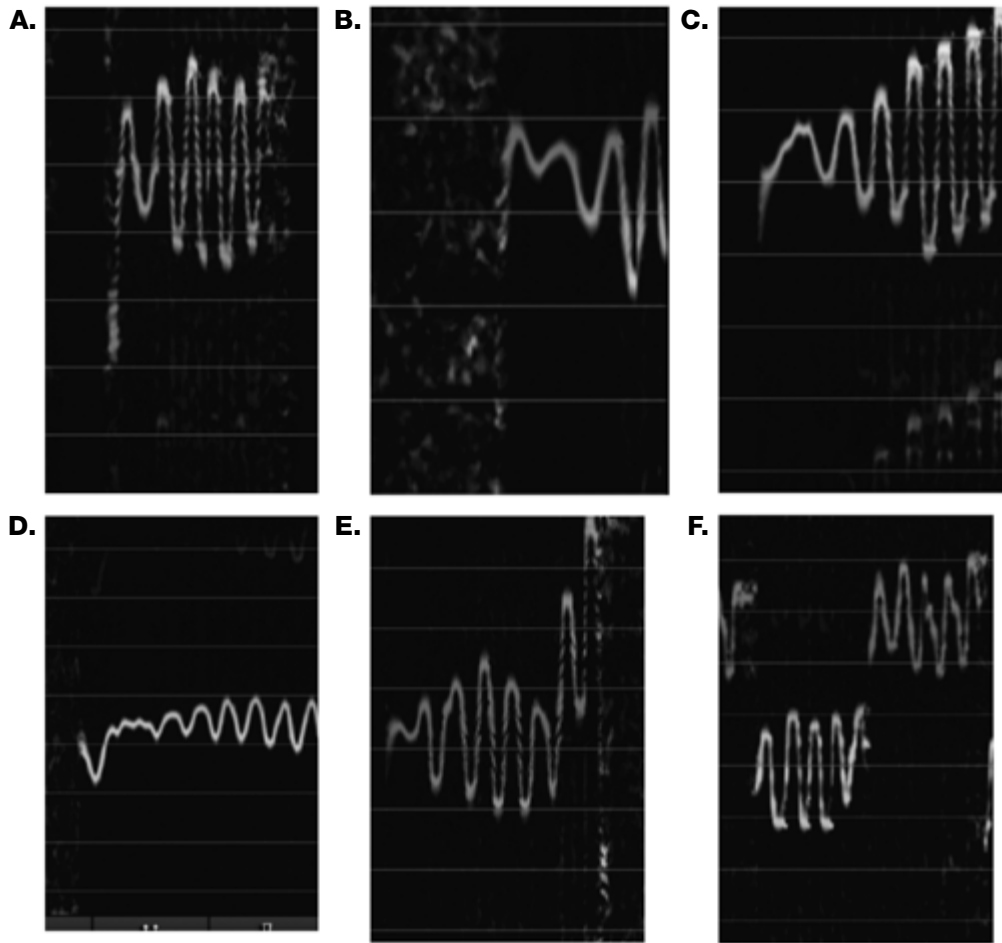
Figure 6. ONSET/RELEASE of selected singers differing in ages and abilities using *PitchLab*. Exercise: various note(s) on [a] repeated 5 times in succession to practice onsets and release.
A. Glottal onset under pitch.
B. Breathy onset (note faint background frequencies prior to phonation).
C. Delayed vibrancy in onset.
D. Onset under pitch and delayed vibrancy (young singer).
E. Pressed release.
F. Balanced onset and release.

LEGATO

Legato phrasing is a hallmark of classical bel canto singing. High level singers usually self-assess vibrancy of sustained pitches and general connection within a phrase. However, vibrant consistency of legato between pitches is very challenging to sense, let alone correct. The teacher with discerning ears can assess this issue, but solving the technical intricacies can be challenging. Once again, visual biofeedback can zoom in on these zones and enable the singer to engage a more fluid legato phrasing. An example is a semiprofessional soprano studying "Un bel di vedremo" from *Madama Butterfly* by Puccini. Beginning with vowels alone, the singer is able to correct the vibrancy of the in-between pitches to create a seamless legato in real time. Subsequently, legato can be refined and observed using the full text (Figure 8). Some of these changes are quite subtle. Recordings aid in elucidating these differences that ultimately have a great impact on the overall quality of sound and ease of production.
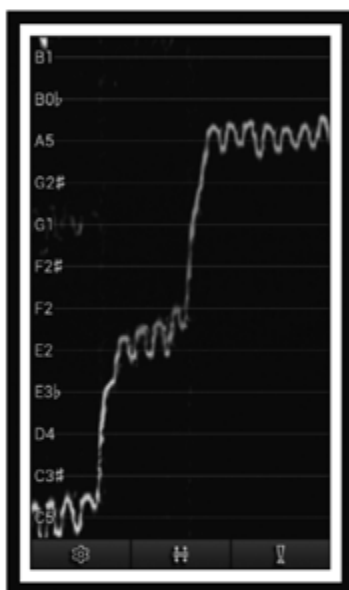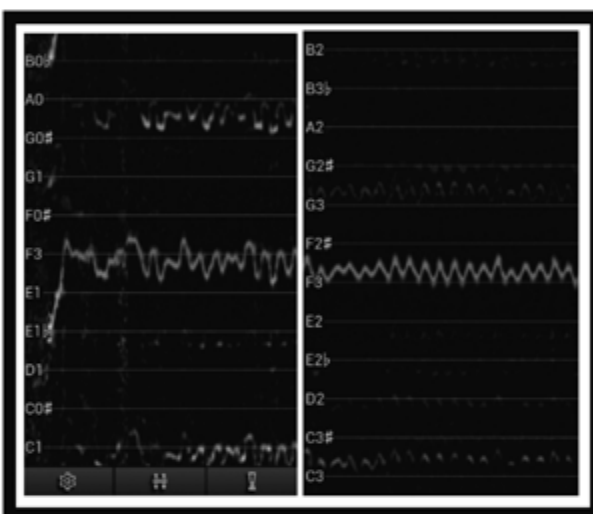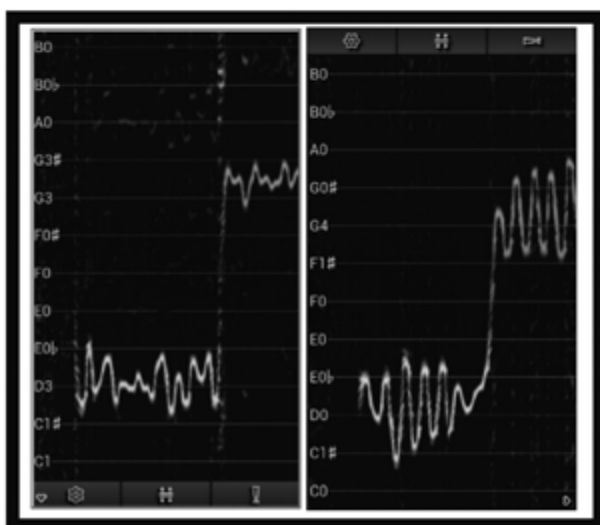
A.
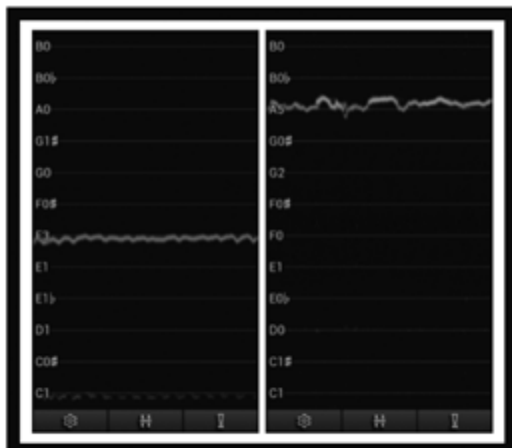
B.
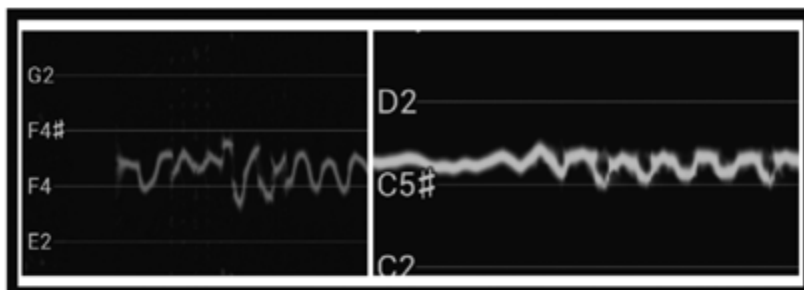
C.

D.

E.

Figure 7. VIBRANCY of selected singers differing in ages and abilities using *PitchLab*.

A. Young soprano, age 12: straight tone choir background experimenting with vibrancy for the first time. Two different notes displayed within one exercise of sustained pitches.

B. Young soprano, age 13: vibrancy improving within a single lesson. Different notes displayed within one exercise of sustained pitches.

C. Young soprano, age 14: vibrancy dramatically improved in one year. Excerpt: Bach/Gounod "Ave Maria," "(e)-et in hora" on [a].

D. Adult Amateur, tenor working on vibrancy awareness and stability singing [i] on F_3 (Note: occasional background overtones will appear if strong, but central signal is still clear).

E. Adult Amateur baritone stabilizing vibrancy in an intervalic exercise. P4: D_3-G_3 on [a].
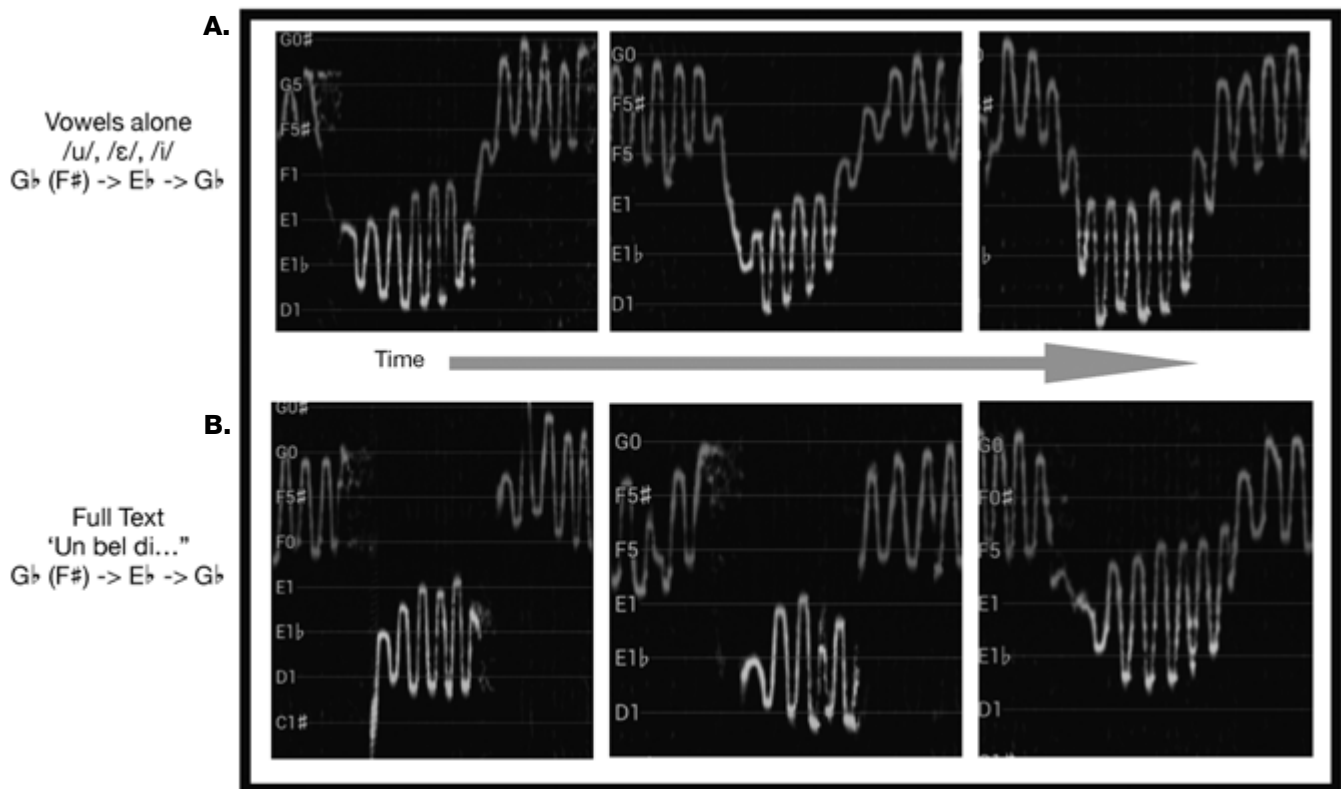
Figure 8. LEGATO, semiprofessional soprano. "Un bel di vedremo" from *Madama Butterfly* by Puccini.
A. **Exercise: sing the vowels only G♭ (F#) -> E♭ -> G♭. Vibrancy in between pitches corrected in real time. (Sounds not necessarily continuous and breaths not represented nor indicated.)**
B. **Exercise: sing text G♭ (F#) -> E♭ -> G♭. Vibrancy in between pitches corrected in real time. (Sounds not necessarily *a tempo* nor continuous, and breaths not represented nor indicated.)**
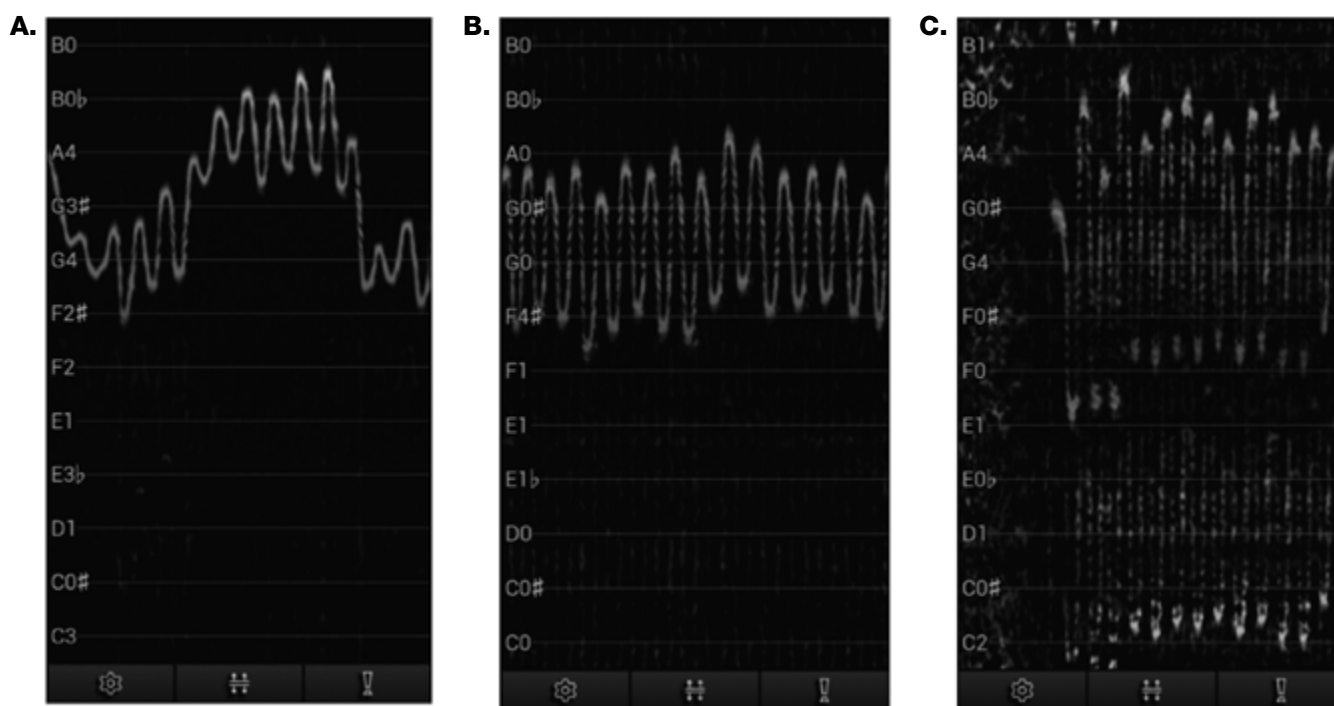
TRILLS

Some of the most dramatic transformations via visual biofeedback has been with singers' execution of trills. Musically the trill (or shake) is a musical ornament utilizing a rapid oscillation between two adjacent notes, generally a semitone or tone apart. A hallmark of the trill is that each note can be identified with the context of the ornament. It can be both challenging to execute and difficult to explain in mechanical terms.

Historically, trills evoke amusing characterizations in voice pedagogy. Pierfrancesco Tosi in his 1723 *Observations of the Florid Song* declared that "The goat-bleat causes laughter for it is born in the mouth like a laugh, and the best [trill is born] in the throat." He also boldly suggested that "he who lacks it will never be a great singer." In 1772 Giambattista Mancini articulated

that "the shake is ruined ninety nine times out of a hundred by too much impatience and precipitation, both in the master and scholar" and has also been quoted saying "a certain rule cannot be found at this moment" [to execute a trill]; Garcia and Lamperti frequently espoused theories on the trill and Garcia's prodigy Marchesi created numerous exercises for the trill, but with little instruction on execution.[9] Exercises and ideas continued to evolve over the years, and even Richard Miller remarked on the challenges of producing a true trill, particularly in relation to vibrato, advising against practicing it excessively.[10] The most exciting data comes from contemporary theories that differentiate vibrato from trill, both at the laryngeal and neurological levels.[11]

The simplicity and success of visual biofeedback in the execution of trills was particularly notable: over twenty experienced singers using this approach

Figure 9. TRILL, postgraduate soprano. All events within a 10 minute period.
A. Exercise: alternate singing G_4 to A_4 on [a].
B. Exercise: trill G_4 to A_4 on [a] WITHOUT looking at visual biofeedback.
C. Exercise: trill G_4 to A_4 on [a] WITH looking at visual biofeedback (some overtones are present; note oscillation rate change).

corrected their trills in less than a minute via visual biofeedback alone. One soprano had been manufacturing trills for years by enhancing her vibrato. As Miller had mentioned, this is a very common phenomenon since the wider vibrato gives an illusion, both physically and aurally, of traversing two notes.[11] However, this strategy lacks the true distance between pitches as well as presents a different oscillation pattern. Given that we now know different mechanisms are required to achieve a true trill, it can be easier for a singer to execute the technique of vibrato already imprinted in their muscle memory as opposed to attempting a new process. Hence, the enhanced vibrato becomes the easiest way to cheat a trill. Figure 9 shows a soprano traversing two pitches a whole-step apart. The singer then attempts to trill and in real time, and is capable of changing from the vibrato state to the oscillation state. Kinesthetic awareness accompanies the visual biofeedback and the recording of the session clearly differentiates the two. The power of visualization to dictate a new motor mechanism is remarkable and gets at the heart of biofeedback success.

ADVANCED SPECTROGRAPHIC ANALYSIS

There are instances where the advanced spectrographic mobile applications can be useful in providing visual representation of complete log frequency profiles for interested students. For example, singers learn the relationship of tongue position to sound by visualizing vowels and their respective frequency identities. In Figure 10 the Audio Analyzer application demonstrates vowels within a wide range of decibels and voice types. It is important to keep in mind these images are for pedagogic and not scientific purposes, however it is possible to optimize, save, and manipulate images for scientific data in Audio Analyzer if desired.

Other applications for the complex spectrograph involve kinesthetic verification, for example, to elucidate aspects of singing whereby perception doesn't match the output. Some singers, especially coloratura sopranos,

may sense a high note as "small" and subsequently over-compensate. In a sense, they actually need convincing that it is acoustically sound and more effective than a pushed note that feels big. This can be done with recordings, but sometimes additional data points are necessary. A semiprofessional soprano who had been struggling with a sustained E employed the Audio Analyzer application to reinforce our work in the studio. In a sample of an ornamented portion of Handel's "Da tempeste" from *Giulio Cesare*, the spectrograph convinced her of its efficacy and she was able to reproducibly sustain the E_6 (Figure 11). This was a great example where sensation countered acoustic reality: pedagogic directives led her to feel the note as easy but tiny, and the spectrograph proved that the note was in fact full, resonant, and in line with the rest of the phrase.

Another example is in the F_1/F_2 crossing that can often be a challenge for male singers.[12] A music theater baritone who was struggling with this registration shift was able to observe the ease and seamlessness of his transition (data gathered over a Skype lesson, clearly demonstrating the quality of the input function of Audio Analyzer). Visualization helped build his confidence and solidify the method of achieving comfort in this part of his register (Figure 12).

OTHER APPLICATIONS

One of the most inspiring elements of my work with visual biofeedback and singing has been its application to unusual populations. Singing is a universal human activity, and I firmly believe that everyone should be able to learn, enjoy, and express through their voice. Not everyone has facility in pitch matching solely from auditory feedback and some individuals are falsely identified as tone deaf, when in fact, less than four percent of the population has true amusia.[13]

As a voice teacher at Google, I came across many amateurs who had small goals such as, "I want to be able to sing 'Happy Birthday'," or "I want to be able to perform on karaoke night." Many of these singers had simple challenges with pitch matching, and others seemingly had no pitch center. Through a pedagogic plan that included everything from intoning in speaking range to singing a childhood song from memory, one of the most successful elements to their regime[11] was the addition
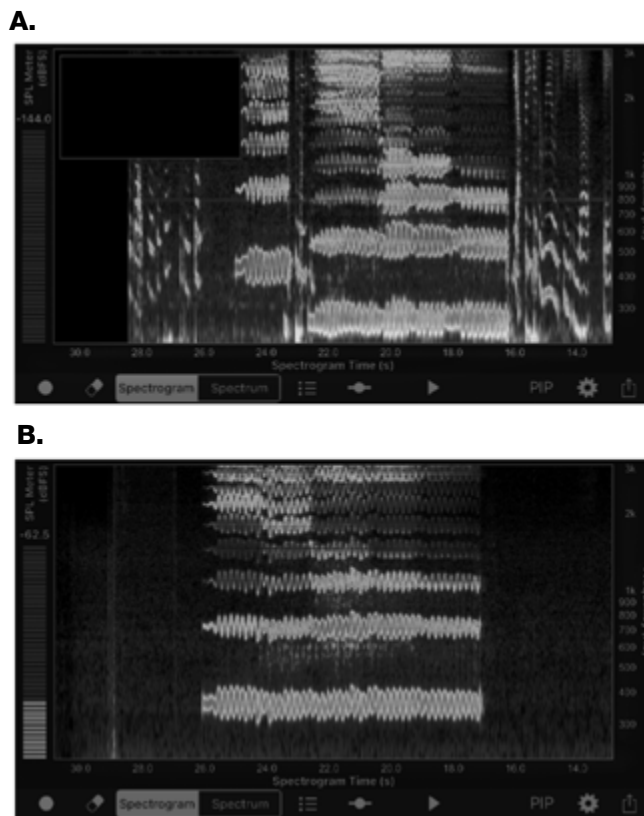
Figure 10. *Audio Analyzer* demonstration of two different voice tyoes singing [i] [e] [a] [o] [u].
A. Heldentenor singing [i] [e] [a] [o] [u] on C_4. Settings are spectrogram with spectrum PIP, 18sec sample. Input calculated to reduce background using the Spectrogram Minimum level (dB) sliding bar and screen-zoomed using touch screen expansion to best fit harmonics profile.
B. Light soprano singing [i] [e] [a] [o] [u] on F_4. Settings are spectrogram with spectrum PIP, 18sec sample. Input calculated to reduce background using the Spectrogram Minimum level (dB) sliding bar and screen-zoomed using touch screen expansion to best fit harmonics profile.

of visual biofeedback. One of the great triumphs came from a singer completely unable to match pitch on day one to performing "Caro mio ben" after only eight weeks.

Another student was a Holocaust survivor who wanted to perform a song for his family on his eightieth birthday. Although his accuracy was reasonable, we were able to refine intervals, vibrancy, and pitch precision through visual biofeedback. To see the joy in song and improving the quality of his voice was an unimaginable gift.
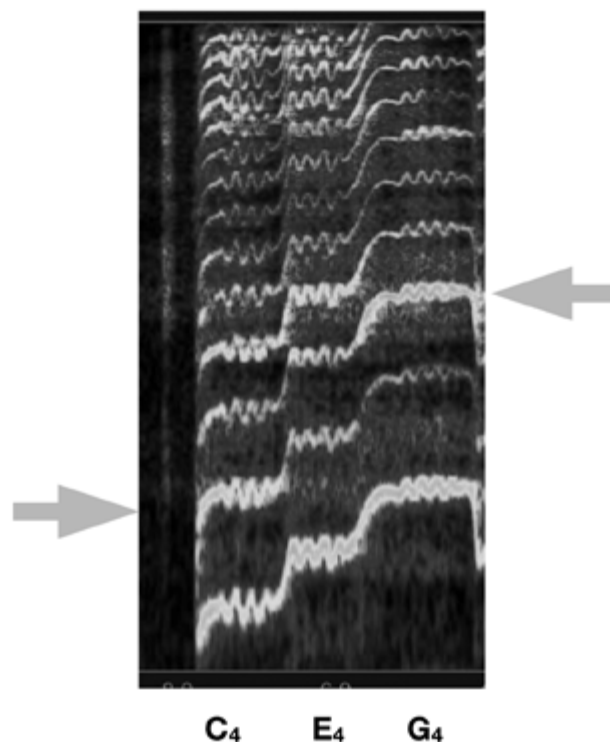
My work with cochlear implant patients was especially inspiring. These individuals are greatly compromised in
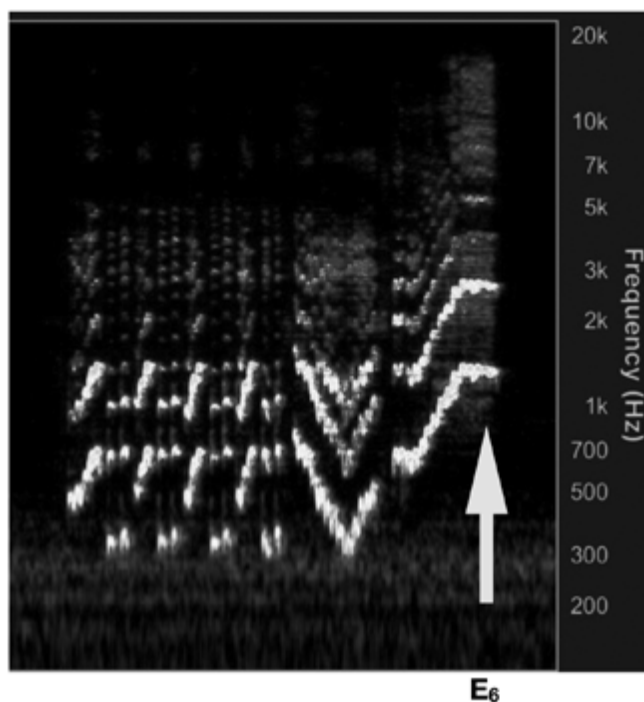
Figure 11. ACOUSTIC VALIDATION using *Audio Analyzer*. **Semiprofessional soprano singing an ornamented portion of Handel's "Da tempeste" from *Giulio Cesare*. Visual biofeedback allowed her to reproducibly sustain the E_6 that she perceives as "easy and small."**

Figure 12. SECURING F_1/F_2 CROSSING using *Audio Analyzer*. **Music theater baritone in Skype lesson singing a C major triad on [a]. Visual biofeedback aided in navigating this challenging region of his voice.**

their ability to match pitch due to the fact that the electrodes to transmit frequency signals are low in number: 16–22 channels compared to 17,000–23,000 hair cells in the cochlea.[14] This results in frequency clusters whereby three to four consecutive pitches can sound like one.[15] Obviously, the result can be traumatic, and even more so to a professional musician.

As part of a MZHF-funded project in conjunction with UCSF, we gathered a group of cochlear implant patients to sing together. One individual had a history as a professional jazz musician in San Francisco, but sadly proclaimed he hadn't sang or enjoyed music in twenty-five years. We had weekly private lessons over the summer utilizing a protocol I had designed coupled with intense visual biofeedback. One of the exercises he enjoyed was to improvise on a short series of notes I would give on the piano. The idea was to allow for some mental freedom, but still in the context of matching pitches. At first, the exercise was difficult and there was little note accuracy. After a few weeks of trials, he

became more confident in his pitch accuracy (Figure 13). By the end of the summer, he eventually performed one of his old favorites, "Fly me to the moon," for the entire group. I recently received an email where he stated his own brain is now actually "hearing" the pitches more accurately, showing that visual biofeedback can perhaps affect the plasticity of the brain's processing of sound. More data is necessary, of course, but this is a wonderful application of the technology and a very promising area of research.

CONCLUSION

The development of convenient, easy to use, and inexpensive spectrograph mobile applications allows students and teachers to utilize the visualization of sound spectra in a new way to target specific pedagogic issues. In many examples the visualization of sound improved the output for various technical directives faster than traditional methods alone. The art of practicing effi-
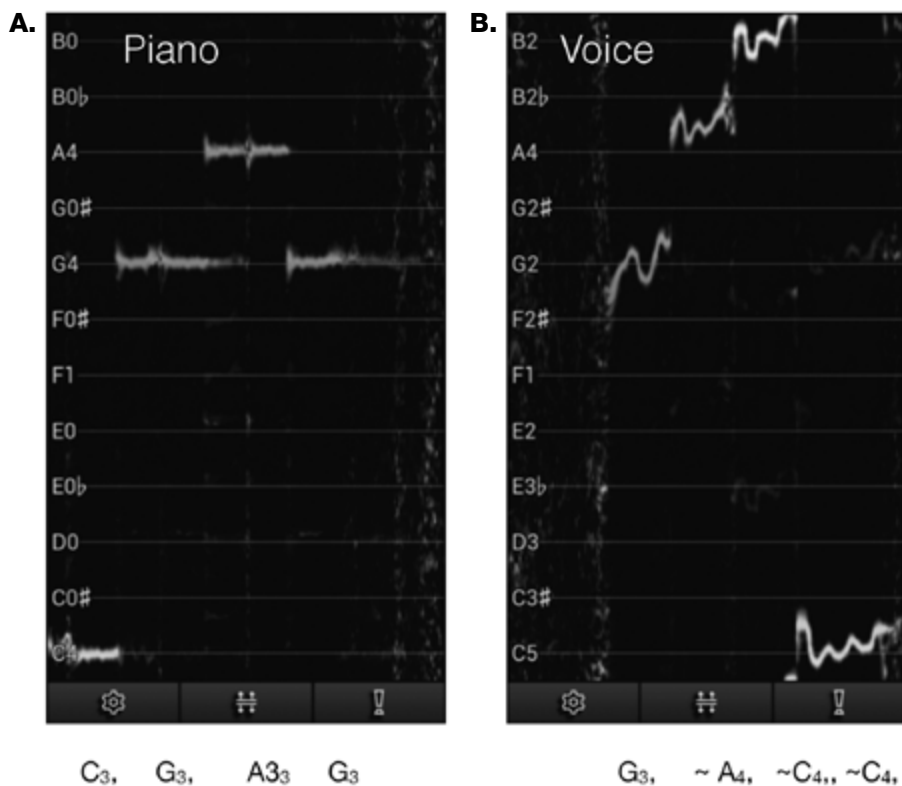
Figure 13. COCHLEAR IMPLANT PITCH-MATCHING IMPROVISATION EXERCISE. A 72 year old Ci patient with previous musical experience, but with severe pitch matching loss, improvising on select pitches on the piano. These results were after approximately two month's work on pitch-matching around C_3.

ciently and effectively is a holy grail in our field, and both students and teachers can easily integrate this technology into their practice to maximize ease and success. In addition, visual biofeedback is a wonderful way to supplement singing instruction to a wide variety of populations, including aurally compromised individuals. More research is encouraged to explore this area in a more scientifically controlled environment, but these early explorations offer hopeful applications to some prominent issues in voice pedagogy. Hopefully, developers will continue to refine these applications to embrace the needs of the voice community.

[Update, October 2020] Pitch Lab by Karl Morton unfortunately was discontinued. Given that it was the best mobile application used for biofeedback in this paper, I solicited other programmers to help design a comparable solution. Thankfully, Bodo Maass, author of the well known VoceVista line of software, has created a template that will be incorporated to both the desktop version and upcoming mobile application release. In my recent beta testing, this version was comparable to PitchLab in its display and sensitivity, but contained far more useful features for singers and teachers, such as record and playback. VoceVista will therefore be the best software available to singers for both biofeedback and analysis in the future.

In addition, I have continued to test applications as they are released. An updated table based on data from January 2021 is featured on the JOS website along with this article.

ACKNOWLEDGMENTS

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Heidi Moss, is a Bay Area performer, educator, and scientist. Noted for her "rich and radiant soprano" (Edward Oriz, *Sacramento Bee*) she has performed on national and international stages, including numerous local companies such as Opera Parallele, Festival Opera, West Edge Opera, Livermore Opera, Fremont Symphony, Peninsula Symphony, Oakland Symphony, and the Sacramento Choral Society.

A champion of new music, she helped spearhead the performance of eight song premieres by eight different renowned composers for an alte/neue lieder fest with LIEDER ALIVE!, including Daron Hagen, David Conte, Kurt Erickson, and Henry Mollicone. She continues her collaborations with living composers including a recital of works by Jake Heggie, with the composer himself at the piano. She has also premiered works by philanthropist Gordon Getty with the Russian National Orchestra and San Francisco Opera and will premiere a piece by Tarik O'Regan next June.

Heidi has also garnered recognition in major vocal competitions, including the Metropolitan Opera National Council Auditions (NYC First Place Winner), the Liederkranz Awards, the MacAllister Awards, and the KDFC competition which resulted in a performance with pianist Lang Lang. In 2019 she was awarded a "Best in the Bay" award for her Richard Strauss recital featuring John Parr of Deutsch Oper Berlin at the piano.

In addition to her musical life, Heidi graduated with a double biology and music degree from Oberlin and a masters in biochemistry at the University of Pennsylvania. She studied telomeres at Rockefeller University and has several publications, including a landmark paper in Cell which was featured in the *New York Times* elucidating a revolutionary discovery that the ends of DNA are looped.

Her interest in voice science came from her work in the lab of the late Richard Miller at Oberlin. Throughout her career, she has collected historical voice pedagogy texts and scientific papers both inside and outside the field to fuel her unique perspective on singing. In 2007, a

rare cranial nerve injury sidelined her singing career, and both doctors and teachers warned her she may not ever perform again. Using her own scientific research and strategies, particularly in how speech and singing is processed in the brain, she rehabilitated to return to the art she loves. She has applied these concepts to train singers of all levels, including those who struggle with auditory processing.

In addition to a private studio, Heidi teaches voice and vocal physiology at the San Francisco Conservatory of Music. She has been an invited speaker at the NATS National Conference, The Pacific Voice Conference, Cleveland Institute of Music, University of Oregon, Vocal ProcessUK, Vocology In Practice, and NerdNiteSF. This year she was also featured as a keynote speaker for the British Voice Association Conference. Her writings have appeared in blogs, such as The Naked Vocalist and in her journal club entitled "Minding the Gap: connecting research from basic science and neuroscience to vocal pedagogy." She is the wife of composer/pianist Kurt Erickson, winner of the NATS Art Song Prize, and they proudly parent 4 children together.

Some are brothers of all mankind,
And own them, whatsoever their estate;
And some, for sorrow and self-scorn, are blind
With enmity for man's unguarded fate.

For some there is music all day long
Like flutes in Paradise, they are so glad;
And there is hell's eternal under-song
Of curses and the cries of men gone mad.

Some say the Scheme with love stands luminous,
Some say 't were better back to chaos hurled;
And so 't is what we are that makes for us
The measure and the meaning of the world.

Edwin Arlington Robinson, "The World"

*= recommended apps as of January 2021

	*Voice Analyst Speechtools LTD	*SingScope *Spingwell*	*AudioAnalyzer Pawel Krzywolzinski	SpectrogramPro *Dominik Seibold*	Nail the Pitch Qiushi Jiang	*Voce Vista Bodo Maass
Cost	$9.99	Free	$9.99	$2.99	Free	TBD (Not yet released)
Fundamental only	YES	YES	NO	NO	YES	YES
Linear Spectrograph	NO	NO	YES	YES	YES	YES
Log Spectrograph	NO	NO	YES	YES	NO	YES
Db and/or waveform	YES	Waveform	YES	NO	NO	YES
FFT and/or Spectrum	NO	NO	YES	YES Bode Plot	NO	YES
Real-time	YES	YES	YES	YES	NO	YES
Record/Play Back	YES	YES	YES	NO	YES in-app purchase)	YES
Touch Screen	YES	NO	YES	NO	YES	YES
Display Quality	+++	++	++++	++	++ (Vibrancy inconsistant)	++++
Ease of Use	+++	+++	+++	++	+++	+++
Gains Adjustment	YES	YES	YES	YES	NO	YES
Overall Rating	+++	+++ Not as sensitive	++++	+++	++	++++