EVALUATION OF COCHLEAR IMPLANT (CI)-MEDIATED MUSIC PROCESSING USING ELECTRODOGRAM MAPPING TO COMPARE WITH PERCEPTION

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EVALUATION OF COCHLEAR IMPLANT (CI)-MEDIATED MUSIC PROCESSING USING ELECTRODOGRAM MAPPING TO COMPARE WITH PERCEPTION

A thesis presented by:
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to the Faculty of the Harvard John A. Paulson School
of Engineering and Applied Sciences and the
Department of Music in partial fulfillment of the
requirements for the Bachelor of Arts degree with
honors in Biomedical Engineering and Music

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"In submitting this thesis to the Department of Music in partial fulfillment of the requirements for the degree with honors of Bachelor of Arts, I affirm my awareness of the standards of the Harvard College Honor Code."

Name: Aaron Hodges

Signature: Aaron Hodges

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Abstract

Appreciating and perceiving music has been a persistent challenge for using cochlear implants (CIs). Despite having speech perception capabilities in quiet environments, CI users struggle with foundational components of music like pitch discrimination and in many cases are unable to enjoy music to the same degree previously. There are a few studies, such as the one by Rubinstein and colleagues where they validated a Clinical Assessment of Music Perception (CAMP) test, that provide a basis for understanding how well CI users can perceive different musical signals. However, most of these studies rely on the surveying and experimentation of patients to determine music perception. This study seeks to provide a methodology that analyzes the spectral differences between musical notes and instruments after processing by the cochlear implant. We hypothesize that comparing cochlear implant processed signals (electrodograms) of different musical instruments and notes will match the performance of cochlear implant users when tasked with distinguishing musical signals from one another.

In this study, we used an electrodogram analysis to visually show how musical signals are processed by a 16 channel cochlear implant speech processor. Signal processing strategies have previously been proposed to affect music perception, so we focused on two commonly used CI programs: HiRes and Optima. We used wav files from the CAMP study that provided comparable pitch and timbre between common instrument families. A correlogram was computed comparing the electrodograms representing musical notes and the notes within an instrumental group was used to quantify the similarities and differences of the electrodogram. This provided an overall correlation, determining which instrument and/or note was the most distinguishable from the other signals. Having additionally investigated music making in the CI community, we hoped to make connections to explain some of the findings in the results.

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1 Chapter 1: **Introduction**

For typical acoustic hearing, sound is transferred through the outer, middle, and inner ear to be relayed to the auditory nerve and centrally to the brain through electro-chemical signals. The ear canal acts as a resonator that causes the tympanic membrane to vibrate, which in turn transfers acoustic energy to the ossicles in the middle ear, which in turn, send a wave through the fluid of the inner ear[1] .The inner ear includes the cochlea, a spiral structure containing the sensory receptor cells for hearing. The cochlea is composed of three compartments: the scala tympani, scala media, and vestibuli. The Organ of Corti, which houses the receptor cells and where the auditory nerve endings are activated, is found in the scala media. For humans, sound is audible from 20Hz to 20000 Hz. The spiral structure of the cochlea is tonotopically mapped, meaning that particular locations resonate best to specific frequencies along the cochlea.

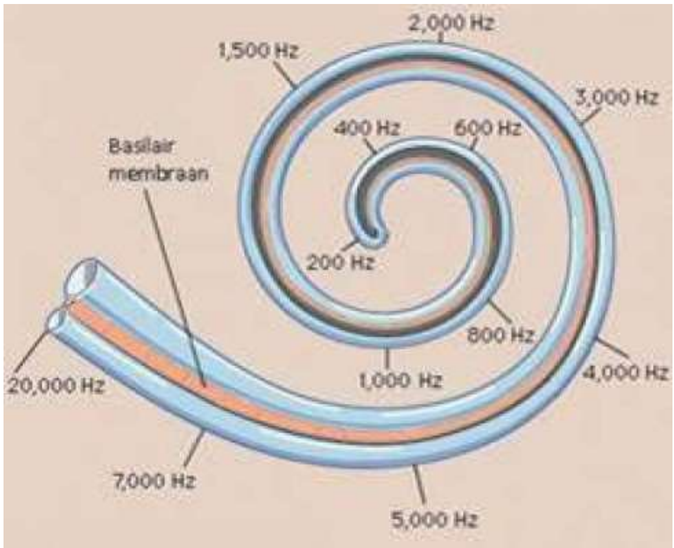

Figure 1.1 Image of cochlea mapped tonotopically[1]

The base of the cochlea resonates to higher frequency sounds and the apex resonates to lower frequency sounds. The receptor cells, or hair cells, in the Organ of Corti are activated by this resonance, leading to a peak in a traveling wave which activates receptor cells thereby transferring a signal to the auditory nerve.

Cochlear implants (CIs) are prostheses for people with moderate to severe hearing loss. CIs are highly successful devices that can yield sound awareness and good speech perception capabilities in quiet listening environments, but many listeners struggle to understand speech in the presence of background noise. A cochlear implant is composed of an external microphone, a sound processor, and an internal receiver with an electrode array. The external microphone receives sound from the environment, which is decoded by a sound processor which determines the pattern of electrical charge sent to the electrode array [2]. Electrical stimulation is initiated by electrodes that are encoded for a subset of sound frequency information to auditory nerve cells that transmit that information to the rest of the brain. CIs take advantage of the tonotopic characteristics of the cochlea, such that electrodes near the base of the cochlea transmit high frequency information while the more apical electrodes transmit low frequency sound information. CIs are designed to bypass the inner ear and directly stimulate auditory nerves fibers through electrical stimulation [3]. Patients must also meet a certain criterion in order to receive a CI. Typically, a CI candidate has severe to profound hearing loss, sensorineural hearing loss. Sensorineural hearing loss is caused by the degradation of the receptor cells in the inner ear called hair cells and/or damage to the auditory nerve cells, leading to attenuation of the intensity of sound that reaches the central auditory system as well as distortion of spectral information [4].

This is unfortunately not treatable with a hearing aid due to the damage in the inner ear, possibly requiring unilateral or bilateral implantation, CIs in one or both ears. Most commercially available CIs have between 12-22 electrodes.

Some technological limitations of CIs include fewer electrodes than receptor cells and conflicting electromagnetic interactions among adjacent electrodes. This interaction can degrade spatial selectivity due to overlapping stimulation of populations of neurons within the auditory nerve [5]. Although some CI listeners' speech discrimination performance approaches that of normal hearing listeners in quiet listening environments, most have difficulty understanding speech in real-world, noisy environments. Listeners also struggle with music perception and tonal languages due to the complexity of the signals and the technological limitations of the implant compared to that which occurs in normally-hearing listeners. Music perception is assessed by how well acoustical information is decoded, especially those that are critical for understanding and appreciating music. For the purpose of my experiment, this would include moving between two different notes (intervals), recognizing chords (harmony and pitch), and identifying the different voices or instruments being played. Additionally, fundamentals of music such as pitch and timbre are impacted greatly by the multitude of temporal and spectral data required for a technical interface to be able to convey-musical sounds. This issue of data is particularly important because many listeners consume polyphonic music with harmony that is reliant on pitch as well as timbre.

There are a few goals I set out to accomplish with my thesis. First, musical signals were visualized as spectrograms and by creating electrodograms, a map of the activity of each individual CI electrodes for the same samples of musical notes from the validated Clinical Assessment for Music Perception (CAMP) test, a peer reviewed music perception test developed by Jay Runstein, M.D., Ph.D., at the University of Washington [6]. Second, through quantifying electrodograms two sound processing strategies were compared to how well musical information would be transmitted to CI listeners (e.g. Optima and HiRes 120). Finally, the results of the electrodogram analyses were compared to CI listeners' CAMP performance data with the same input signals, to determine connections between the success of the CI user and activity within individual channels.

Music appreciation in CI users is often low, perhaps due in part to challenges in music perception. Additionally, similar to normal hearing listeners, CI users have a variety of individual preferences, indicating that finding a single solution to this problem might not work for everyone. This project explores these questions by building a basis for analyzing individual mapping data of CIs for musical foundations with the long-term goal of improving music perception and appreciation. The data from this project will further illuminate what frequencies of sound and timbre of instruments are more accurately processed through CIs with different signal processing strategies. This will hopefully provide guidance on how music can be catered to CI users. Instead of relying on the eventual improvement of CIs, working with the current limitations of the device would be beneficial for CI users that want to enjoy music currently. It may be useful to facilitate the information as a way to compose music for CI users. As a composer and musician, I would like to personally explore these findings to determine what music appreciation means when an individual hears the world differently. Through these questions, we can begin finding ways to create music that may be garnered towards individuals with CIs.

2 Chapter 2: **Understanding the Deaf and Cochlear Implant Communities**

2.1 Connections with Deaf Culture

One facet that many physicians have overlooked in order to solve the problem of music perception in Cochlear Implant (CI) users is studying the Deaf community. To start, there are various degrees of deafness that impact how effectively a potential CI user will experience sound, especially music. For instance, being born deaf or developing deafness in adulthood have different consequences of how successful an individual will hear sounds, speech, and music after implantation. There are countless studies that have indicated a higher success of enjoyment of music for prelingually deafened children after receiving a CI[7]. Since they have limited experience with sonic spaces and language, learning music through the CI is what they know. Earlier implantation has been shown to be advantageous in the growth of learning languages and having higher appreciation towards music[7]. Considering how this impacts hearing, it becomes evident why individuals who become deaf in their adulthood or receive an implantation much later experience sound much differently. Having memories of music and language before deafness or learning how to navigate the world without hearing or decreased hearing for a long period of time impacts how we interact with the world sonically. There are many people who do not consider deafness a disability but embody Deaf culture. Thus, the Deaf community is a diverse group of individuals with their own culture and identity. Some choose to get CIs and some choose to be a part of Deaf culture.

Furthermore, CIs were created to allow deaf individuals to perceive sound. Many of the solutions engineered to attain this goal have focused primarily on the device itself (such as the electrode array design or signal processing). However, none of these approaches have considered the factors described above such as why CI users are able to perceive particular sounds better than others. In addition, investigation into how sound is retained or evolved in compositions by the Deaf community could provide insight into the success of perception after receiving an implant. Analyzing how the Deaf community creates music could point towards improvements and solutions in CI technology and considering this community's work with sound seems critical (considering physicians seek to help people with hearing loss). It may also provide evidence of particular sounds we should be exploring in cochlear implants to understand how to improve perception.

Unsurprisingly, there appears to be no single way that the Deaf community creates music. Compositions range from interpretive videos of pop songs incorporating American Sign Language (ASL) to original compositions emphasizing the expressiveness of ASL. Many of these works however are not created exclusively by the Deaf community. This is especially the case in interpretive videos that translate videos for the Deaf community or even non-deaf individuals who use ASL as an artistic form of expression. This is why some musicologists choose to separate works from Deaf culture into four categories: Live Music Interpretation Services, Live Performance by Song-Signing Artist, Videos Featuring the Performance of an Original Song, and Videos Featuring the Performance of Pre-existing Songs. Live Music Interpretation Services primarily functions as a translation of song lyrics for the Deaf by hearing people. This is usually professionally done in a concert setting or in a church for example. Live Performance by Song-Signing Artist and Videos Featuring the Performance of an Original song are both typically led by Deaf musicians for a Deaf audience. Videos Featuring the Performance of an Original Song sometimes are solely performed in sign languages, while others include a vocal line or even musical instruments. Videos Featuring the Performance of Pre-existing Songs is the most common and primarily features hearing performers. This category typically entails amateur homemade videos creating a "playful" and dancelike rendition of popular music through signing. Although they are not all encompassing of every possibility, each of the categories allow a clearer delineation between how individuals who hear interact with music in Deaf culture and how Deaf individuals make music [8].

Parsing out what happens in these four genres enables us to see how hearing and Deaf individuals interpret the use of sign language. This offers an interesting perspective of what qualities of sound are retained in the Deaf community's music. Even without the ability to hear in the same form as hearing individuals, there are some aspects of music that remain fundamental to the compositions that the Deaf community creates. There are also components that do not prove to be as important to the Deaf community and are more prevalent in the translations from hearing individuals as shown through the content of their music.

One example is how hearing signers try to convey pitch and register through altering space changes with ASL. This could be shown through the tilting of the head to represent the particular octave of a passage. This has also manifested into pulsing of different parts of the body to maintain the tempo of a song [8].

This direct translation of rhythm or register into haptic symbolism (the body pulses to rhythm, a head tilt conveys as a register change) is however not as prevalent within interpretation of Deaf individuals. Many Deaf performances put greater focus on space as the expansiveness of ASL, meaning there is no direct 1 to 1 translation in the art form being displayed. The symbolism is imbued with deep emotions and a context that is not just evident in the lyrics, but also within the musical and sonic content. H-Dirksen L. Bauman (2006) describes this as ASL, "composed of lines, invisible and kinetic. … The line carries a generating capacity, an expressiveness all its own whose speed, tension, length, direction and duration construct and disperse a particular energy". Therefore, there is greater emphasis on how movements create a greater meaning of expression to convey a message. There usually is not a representation of pitch or register, but rather the dynamics and contour of a piece. This description personally reminds me of how musicians refer to different colors that arise when setting the tone of a musical piece. Instead of thinking of music in terms of music theory, progression, and voicing, shaping the piece by evoking a particular "color" allows unique and unprecedented harmony to form. Improvisation is a good example of this transcendence of traditional form, relying on the "color" or feelings of notes. As the jazz pianist Art Tatum proclaimed, "There's no such thing as a wrong note," when it comes to improvisation. The first step to becoming more familiar with improvisation is recognizing the uncontrollable and infinite expanse that it entails. This is why it is necessary to identify fundamentals that will allow you to navigate your individual way of improvising music. Although there are multiple possibilities on how to begin, a helpful basis can be starting with something you are familiar with or learning from another individual. Learning from someone else is beneficial because in many circumstances improvisation is sparked from an interaction between musicians.

Improvisation can be viewed as a "collective intention" caused by "the convergence of individuals" that result in non-preconceived music [9]. Inspiration from the sound of other musicians creates a feedback loop that causes a transfer of ideas that can lead to creating something new. You could also individually experiment with a motif, a scale, or a particular sound. Emphasizing this further, there is not a single way to rediscover and reconfigure this musical idea. This process can be described as "horizontally inexhaustible" meaning "unlimited" and able to demonstrate "infinite creativity" [10]. This is what allows you to never play something the same way despite deriving inspiration from something that is already known. The "collective intention" is also not limited to the performers on stage. The audience listening and feeling the music is just as integral to the sound that is created. A common phrase to express this concept is "feeding off of each other's energies" and incorporating the atmosphere into musical ideas. Vijay Iyer beautifully describes this phenomenon as music embodying "the sound of human bodies in motion", reflecting on each person's aurora and responding innately or outwardly [28]. He even goes as far as describing human connection through improvisation scientifically to "mirror neurons" that are known to be involved in human empathy and understanding. As a result, the reflection of the collective is informative of the "color" of the piece or the mood that manifests as the performers plays and the audience interacts.

For me, I implemented both of these techniques when I initially started improvising. Improvisation did not click until I learned from a jazz pianist who taught me the F-blues scale. Instead of focusing on the traditional purpose of improving virtuosity of technique moving up and down a scale, my mentor challenged me to experiment with rhythms and skipping across notes on the scale. Eventually, I realized that his recommendation also wasn't limited to just notes in the scale itself. Overtime, I continuously experimented with different ways of playing with this scale until eventually I was able to come up with a composition that changed each time. Continuous change of the piece and the passing down of knowledge from my mentor highlighted how I could never finish my piece. However, continuously working on my evolving composition was a way I could progress and formulate my own understandings of improvisation.

Rosa Lee Tim, a Deaf artist, demonstrates this by their interpretation of Carrie Underwood's "Blown Away". "Rather than focusing on the representation of register through her signs, Timm uses the signing space to represent the more intangible sense of rising intensity and anger in Carrie Underwood's music, and to leave us with a new interpretation of the song's ending" [8].

There are other examples of current Deaf composers that epitomize the way music is created in Deaf culture. These musicians include the rock group Beethoven's Nightmare, the Detroit deaf rapper Sean Forbes, and the Finnish rapper Signmark [11]. All of these groups make music within the Live Performance by Song-Signing Artist and Videos Featuring the Performance of an Original Song category due to their Deaf audience centered music. They also represent a wide variety of Deaf experiences. Sean Forbes became Deaf at only a few months old, Signmark was born Deaf into a signing family, and Beethoven's Nightmare was originally the first band with all Deaf members. Each of these groups incorporate ASL into their works and convey the experience of a Deaf individual in a predominantly hearing world. Some of them, in particular the band Beethoven's Nightmare, have an emphasis on playing instruments and using the feelings of vibrations to create a song. Although Beethoven's Nightmare did eventually recruit players that could hear to help create the vocals and pitch based songs, members of the band have noted in the past the importance of "feeling the music" affecting the way they perform. Bob Hiltermann, the drummer of the group who is Deaf, stated, "The way I play, I depend on a lot of vibrations, so we play really, really loud, enough for us to hear and feel it"[11].

Anecdotes of Deaf musicians using the vibrations in the floor or from their instruments have been noted as far back in history as Beethoven's experience as he began losing his hearing.

Unfortunately, there is a lack of literature and research noting the practice of how Deaf musicians *translate* these vibrations into compositions. Scientists like Dr. Charles Limb at the University of California, San Francisco have begun studying Deaf musicians playing music through fMRI studies, but there are no cross studies studying the effects of vibrations translating to music. There would be a huge benefit in understanding music cognition and perception when it comes to varying frequencies of vibration. This vibrational ecosphere could be thought of as representing a "new form of hearing" and we would then need to reconsider how the sense of touch can compensate for not using the human ear.

There are some studies that have attempted to document an increase in tactile sensibility within Deaf individuals. A crucial connection that may arise from these findings is why cochlear implant users are able to perceive musical rhythm better than pitch and timbre, and does deafness engender a hypertrophic sense for rhythmic complexity? Evelyn Glennie, a Deaf Scottish percussionist, in a Ted talk gives an example of the phenomenon of acquiring musical information through the vibrations of an instrument:

> *And I remember when I was 12 years old, and I started playing timpani and percussion, and my teacher said, "Well, how are we going to do this? You know, music is about listening." And I said, "Yes, I agree with that, so what's the problem? "And he said, "Well, how are you going to hear this? How are you going to hear that?" And I said, "Well, how do you hear it?" He said, "Well, I think I hear it through here." And I said, "Well, I think I do too, but I also hear it through my hands, through my arms, cheekbones, my scalp, my tummy, my chest, my legs and so on." And so we began our lessons every single time tuning drums, in particular, the kettle drums, or timpani to such a narrow pitch interval…And it's amazing that when you do open your body up, and open your hand up to allow the vibration to come through, that in fact the tiny, tiny difference can be felt with just the tiniest part of your finger, there. And so what we would do is that I would put my hands on the wall of the music room, and together, we would "listen" to the sounds of the instruments, and really try to connect with those sounds far, far more broadly than simply depending on the ear. Because of course, the ear is subject to all sorts of things. The room we happen to be in, the amplification, the quality of the instrument, the type of sticks -- Etc., etc., they're all different. Same amount of weight, but different sound colors. And that is basically what we are; we're just human beings, but we all have our own little sound colors, as it were, that make up these extraordinary personalities and characters and interests and things…*

Although she is unable to hear the sound coming from something like a snare drum or a marimba, Glennie describes the distinction of vibration that she feels when striking each instrument. She explains the methodical practicing she endured in order to feel the differences between intervals on a marimba or the clicking of the rim on a snare in contrast to hitting the drumhead. She is therefore not relying on muscle memory and recollection to recall where to strike the different notes on the marimba. Glennie understands not only rhythm but also pitch through painstaking practice of elucidating subtle vibrations. Of course, Glennie is quite the exceptional musician to accomplish such a feat but understanding how she's able to differentiate pitch through mere vibrations could be worth investigating.

Research has also pointed towards this enhanced ability to perceive through touch as a product of cross modal plasticity. Cross modal plasticity is the reorganization of neuron connections between functions of two or more senses due to sensory deprivation in a part of the brain. MRI studies have been able to show activity within the auditory cortex when an individual receives vibrational stimulus through a loud speaker or plastic tube [12]. Other literature have also pointed towards greater sensitivity in sudden tactile vibration changes that is more unique to Deaf individuals [13]. This may explain Glennie's amplified ability to distinguish notes through the vibrations she feels from the instruments. Through these vibrations, Deaf individuals are also able to maintain tempo and perceive rhythm changes even before receiving a cochlear implantation. Tactile sensitivity may be a means to explain retention of rhythm perception and may be an avenue to improve perception of other fundamental properties of music.

Unfortunately, I was unable to find studies that consider the link between music composition and vibration perceptions of Deaf musicians. For example, it would be interesting to determine what frequencies of sound are used most often in compositions by Deaf composers. This would provide insight into what vibration frequencies the Deaf community tends toward or incorporates into their music. There may be an underlying reason behind these musical choices in Deaf culture music and what is perceived through vibrations. Something that would benefit this area of research would be a case study that tests the music making process of a deaf individual. Even exploring preference of Deaf composers to what vibrations they prefer would answer musical appreciation questions that are still unknown. Possibly retaining what we know about the perception of vibrations in the Deaf community could translate to perception of sound into cochlear implant users.

2.2 The CI Community

Considering that the Deaf community interacts with sound and music quite differently from the hearing world, it is worth considering Cochlear Implant (CI) users as having their own unique experiences as well, unlike either the hearing world or the Deaf community. Instead of trying to strive to improve the device to match what we consider “normal hearing”, it might be worth figuring out what sound or sonic practice will improve music appreciation for people who use CIs. Expecting CI users to eventually appreciate music the same way as people with acoustic or normal hearing may not be the best approach. As some scientific literature has pointed out, more research should be conducted into engineering or manipulating music that is specifically composed for CI users. One study in particular found that altering music, whether to be more simplistic or have a particular instrumentation, had greater preference by CI users than listening to the original piece [14]. CIs have limited range and accessibility to sound, so it would be reasonable to try to alter music that is geared towards its functions. That way it can be more pleasing for the CI user, and further investigation can give us greater insight towards music appreciation.

Cochlear implant (CI) users are a growing community of over 400,000 as of 2014, with numbers estimated to be as high as 600,000 present day [15]. The growing community makes it even more important to prioritize music appreciation, which at times is dependent on how well sounds can be comprehended.

Surprisingly, a research survey of 65 post lingually deaf CI users that rated music enjoyment has shown that listening using CIs can have a significantly negative effect on music enjoyment. These individuals with prior experience who nonetheless treasured music before implantation seem to lose their relish for musical sound. Ratings dropped from 8 before implantation to 1.93 after implantation on a scale from 1 to 10 [16]. Total listening time has also shown to decline as demonstrated from a survey where 68% of users listen to music for 3 or more hours before implantation to 62% listening for only 2 or more hours after implantation [16].

This however has not deterred many CI users from wanting music in their life, with over 37% of users being willing to undergo implantation if that meant just being able to listen to music [16]. Thus, I am interested in researching what is effective at retaining music appreciation for CI users. If perception is limited in the current device, how has the CI community prevailed past this and what work is being done to allow CI users to enjoy music? Current auditory research emphasizes improving CIs to achieve “normal hearing” or as close as possible. However, there are some composers that have challenged this notion by creating music that is tailored for an audience of CI users. Composition for CI music is typically electronic based and incorporates speech, percussion, or low frequency sounds as studies have shown the highest perception for these sonic sources**.** However, music perception does not guarantee an individual will enjoy or appreciate the music they are listening to. That is why understanding music appreciation helps us understand more of the experience of listening to music through CIs. It will therefore be important to not only analyze the music made for the CI community, but also interview CI users to find similarities that may reveal ways to improve music enjoyment.

But before considering CI users and music in greater detail, it's important to reflect briefly on the ideological questions that have arisen with CIs. Being that CIs were invented to restore hearing of moderately to profoundly deaf individuals, the Deaf community is closely interrelated with the CI community. Deaf culture has its own traditions and history that may even affect the decision of an individual to receive a CI. In the past, there was quite a controversy on CIs being portrayed as a "cure" to deafness. Deciding whether or not pediatric implantation of the device was ethical due to concerns of "Deaf ethnocide" came at the forefront of this argument [17]. The Deaf community was concerned that new CI users would begin to not identify as deaf and eventually affect Deaf culture as a whole. Fortunately, the National Association of the Deaf (NAD) has been clear about accepting not only an adult's choice of undergoing the procedure for CIs, but also educated parents who decide for their child. A study by the University of Colorado showed that caregivers were given information and a chance to interact with the Deaf community, allowing families to factor this into their decisions [17]. CI users have therefore become their own community, choosing whether to identify with the Deaf community or defining culture and interaction with sound on their own terms.

2.3 CI User Musical Practices

The variety ways of how CI users identity and interact with music makes each individual experience quite different from another. There are no particular instruments or ensembles associated with CI users because they are able to be a part of so many different communities. There is one example of a drumming group founded by an implantee named Sarah Smith who hosts a local ensemble for CI users in Southampton in the UK [18]. “Drumming for Cochlear Implantees” encourages music appreciation and further exploration of CI capabilities.

Currently, most examples of CI users’ music are displayed by joining a musical group that is not predominantly CI users or relearning how to hear. Composing music for cochlear implants is a relatively new idea that mostly has been conducted by researchers and experimental musicians. There has been an emphasis on improving music perception not through engineering of the CI device itself, but through manipulating music so that it is conducive to how CI users currently hear. The technicality of sound engineering and changing music within the parameters of a CI device makes it challenging for a CI user to make these compositions. The few that are available were commissioned by the Bionic Ear Institute located in Melbourne, Australia. The Bionic Ear Institute specializes in medical devices that restore function to impaired sensory organs in the human body. In 2011, the Bionic Ear Institute was particularly interested in finding ways to compose music specifically for the cochlear implant (CIs). As a result, a group of 6 musicians including Ben Harper were tasked to tailor and manipulate sounds that would better allow people with CIs to perceive and appreciate music [19]. These pieces were predominantly electronic works with prerecorded instruments such as piano, cello, and percussion. Many of them also incorporated speech and experimented with sounds through example sound processors that replicated cochlear implants. These pieces serve as a direct way to analyze the techniques used to address scientific research that has been conducted on music in CIs.

The 6 pieces were premiered in 2011 at the George Fairfax Theatre in Melbourne. A survey was shortly conducted afterwards to gather a response from recipients at the concert.

Overall, normal hearers and CI users were found to have similar levels of enjoyment ratings for the pieces. The highest rated pieces for CI users however were the pieces that integrated percussion and voice, which was expected from previous research [19]. The concert became a direct example to show how perception impacts the appreciation of a piece. The two pieces that exemplify the results from the survey are "This is All I Need" by Ben Harper and "Study for the Bionic Ear #1" by Natasha Anderson**.** Ben Harper's piece focuses on auditory research findings that speech can be perceived more easily due to voices having consistent voicing frequency. Using only the 1st and 2nd formants (harmonics that come from the vocal tract) is enough to be transmitted successfully through cochlear implants [19]**.** Using this information, Harper treated the piece as a "primer to a new language" due to speech having better perception for cochlear implant users. Thus, the leading voice followed by a melody with a similar rhythm to the annunciation in speech is used prevalently. Harper also created unusual harmonies as a result of using16 tones instead 12 tones used for chords in the piece. The 16 tones represent the tuning that is based on the frequency bands of the cochlear implants, the lowest being 250Hz. Natasha Anderson creates a style that incorporates rhythmic cues that are mostly maintained in cochlear implants. CI users are able to perceive rhythm almost as closely as normal hearers due to the accuracy of being able to replicate amplitude envelope patterns (the change of amplitude over time) [19]**.** Anderson also deliberately uses sounds of playing solo as well as changing pulse rates that have been shown to affect the perception of CI users. For example, the pulsating in the vibraphone is very reminiscent of vibrato in a wind instrument while pulses in the tom drum are very rhythmic. Pitch was also kept in mind as having similar qualities to how tones sounded when played through a CI simulation. Both of these pieces may reveal other aspects that allowed CI users to better understand and enjoy the music.

2.4 CI User Interview

As many of these studies have shown, one of the most important aspects of learning about the CI community is directly asking people. Music appreciation and perception vary drastically between users, so working with a community will be the best way to improve the device. Interviews will therefore be an important part of my research to get the perspective from a CI user. While researching, I was able to interview Charles Hem, a PhD candidate at the Speech and Hearing Bioscience and Technology program. Charles had only received his implant a year and a half ago and alluded to particular themes that will be important to reflecting the various experiences of CI users. Hem was very clear about his use of residual hearing, or ability to use his still functioning left ear while adjusting to the CI. As a result, he expressed his "disappointment" after receiving the device having been under the impression that it would restore him closer to normal hearing. It was really interesting to learn his perspective on the lack of a CI community because "there is no unifying language, like ASL in the Deaf community". Hem identified more with the hearing world and in many ways did not meet the expectation of drastic hearing changes that are associated with CIs.

2.5 CI Conference Testimonies

There are also some testimonies from CI users for the Cochlear Implant Symposium in 2018 showcased in Montreal, Canada. The symposium brought together scientist from around the world determined to bring music to all CI users [20]**.** From the conference, three testimonies with the approval from three CI users that are deeply invested in music were showcased.

Bettina Gellinek, a piano teacher, relates in her testimonial video that she had recently been implanted 6 months ago:

> *I've had a gradual progressive hearing loss over the past years or so and my formerly rich musical life had completely shrunk a couple of years ago. I had to give up teaching children because I could no longer understand their speech or their mothers. I also continued to take piano lessons myself even while only hearing clicks in the high range of the piano and a struggle was what I call soundsoup when I played more complex or corridor passages…My implant surgery was only six weeks ago and to have been activated for two weeks, I already understand speech very well again which has surpassed all my expectations. My main concern in getting the implant was of course music because I understand that cochlear implants are not geared toward pitch but the less I had to lose and the worst music sounded already the more I was willing to take this risk…*

Overtime her implant allowed her to enjoy the things she once loved doing like teaching, despite initially being afraid she would lose music due to the limitation of CIs.

Renee Blue O'Connell, a musician for over 45 years, was implanted 9 years before her video testimony. Renee explained how painstakingly she worked to train her ear, going through timeless repetitions of interval recognition and sight singing. This allowed her to rejoin her choir, slowly begin recognizing harmony, and become a certified music practitioner.

Lastly, Alek Mansourin, a 23-year-old music student who was implanted in the 7th grade and eventually in both ears, also shows how training yourself to hear with a cochlear implant over the years allowed him to study to become a music performer:

> *I've had to get over…pitch problems with noise filtering instruments you know like if conductor says listen to the clarinet or listen to the oboe it's sometimes very difficult to just do that as a naturally deaf person and I've found that the way I can get through this is at night I will play recordings of that instrument to familiarize myself with it…I think familiarity and consistency are our keys in implant development and what patients need to be looking for in their devices…the way I've become familiar with pitches is by basically playing with recordings of pitches. Another exercise I found myself doing to help train my implants in the performance process has been playing with a piano singing with a piano and I'll start with a simple exercise one with simple fits and I'll sing trying to go in and out of the correct pitch to hear where I am in relation with the correct pitch when I come back to the correct pitch. On the second time around, it settles in rather than grabbing it out of thin air because my ears are aware of what of what the sound is. This applies to trombone because now I can hear what the sound is…*

Alek emphasizes the difference sleeping with a CI made for improving his music perception and encouraged researchers to directly involve CI users and himself in being beta testers for new studies. Each of these individuals bring a unique story that prompted me to want to ask the following questions to my proposed interviewees. 1) Has the CI brought you together with other individuals with CI, and if so, what things have you learned from one another? 2)Are there any particular sounds you find enjoyable that you didn't before? 3) Has having a CI changed your perception of deafness? Do you identify still being Deaf?

We still have a long way to go in terms of addressing music appreciation and perception in the CI community. Despite this, CI users have shown their ability to continue their passion for music and even challenge what music should sound like. Interviews give insight to how experiences of hearing through CI can vary tremendously, but also bring a new way of hearing. The more conversations that are had, the more we can better understand that CI community as its own culture and experiences sound and music differently from others.

3 Chapter 3: Methods and Results

3.1 Methods

The first objective is to create electrodograms using the musical sound samples already validated and used in the Clinical Assessment of Music Perception (CAMP) test [21]. The electrodogram is a representation of cochlear implant processing of sounds made by different instruments and allows the quantification and visualization of how CI channels are stimulated for each. The CAMP test is a previously validated paradigm that assesses CI users' music perception ability. The CAMP music excerpts are used to computationally map channel activity to determine the representation of pitch change, melody, and timbre through each individual electrode. Additionally, electrodograms represent the intensity and timing of signal output through each of the individual electrode channels for a particular speech processing strategy. The color map, based on the amount of current, shows a clear effect of different parameters such as signal processing strategies, dynamic range of patients, and pulse rates. Electrodograms are underutilized tools that could be one of the first assessments to determine how a stimulus like music is processed by the CI. The samples from the CAMP study used for this study were short 5 note sequences from instruments from well-known musical families [6]. I hypothesize that the similarity of electrodograms may indicate musical signals that are challenging to discriminate for CI users.

Creating the electrodogram involved using a coding program called BEPS+, software provided by Advanced Bionics Corp. to Mass Eye and Ear. The program allows the user to change the parameters of speech processing strategies. Using MATLAB, the program data from BEPS+ can be converted into an electrodogram and plotted using the image function for each of the instruments and musical notes from the CAMP Study.

3.1.1 Stimulus Wav Files

To have a basis for exploring CI data, I reached out to Jay Rubinstein to obtain the wav files from his Clinical Assessment of Musical Perception (CAMP) test. Dr. Rubinstein had already used these files to conduct perceptual tests of timbre and pitch for CI patients in a previous study. Each file contained 5 different notes for each instrument played in succession in 3 second wav files. Eight total instruments were used to simulate various pitches, spectral data, and timbre: Cello, Clarinet, Flute, Guitar, Piano, Saxophone, Trumpet, and Violin. Real time recordings were facilitated, and each musician from the CAMP study was instructed to play the same articulation, tempo (82 beats per minute), mezzo forte dynamic, and phrasing. The notes middle C4, A4, F4, G4, and high C5 were played in succession on the recording for the same duration. Further information can be found in the original study [21]. The number next to the note name is known as scientific pitch notation. It indicates and location the position of a note on a staff ledge line and based on the octave of the note. Additionally, modifications were performed on the wav files of the instruments such as root square mean and peak normalization. The purpose of using the CAMP wav files was to compare the findings for the University of Washington (UW) study to the statistical analysis of this thesis. I also found samples of the same notes and instruments from two other sources: 1) The UK Philharmonia located in Southbank Centre, London (referred to as Philharmonia (Phil) in this paper)[22] and 2) The University of Iowa Electronic Music Studios (referred to as Iowa in the paper) [23]. Both of these sources had their musicians create live recordings that were the same notes and instruments as used in the CAMP study. I chose the samples that closely resembled the same instructions as the CAMP stsudy, although this was not entirely the same. However, in the real world, musical stimulus changes, instruments can be played in some many different. This is far more reflective of a real world scenario. We are therefore able to have a guideline of what the correlations mean and how significant the results of comparing the different instruments and notes through correlation. Each of these samples were treated the same way and normalized as described in the next paragraph to have consistency for analysis.

For the CAMP, Philharmonia, and Iowa, a 200ms window was sampled from the middle of the sound files to capture a steady state of the sound and prevent identification from the attack or tail of a note alone. The software Audacity was used to normalize the peak of the wav files to -5dB calculated based on the average peak of all the CAMP wav files. The perceived loudness was also normalized through Audacity to -12 dB by calculating the RMS of the CAMP wav files. When computing the electrodogram, the data of each instrument was averaged into 120 time bins (approximately 6ms a pixel for the total 200ms of the wav file). The intensity of each of the channels is measured in microAmperes for all 16 channels. The higher the intensity, the redder the color of the electrodogram channel.

Through this grouping, we can also determine the effect of including temporal data of the wav files. Before calculating correlation, the overall intensity of the electrode channel can be averaged or kept in the 120 element bins. Checking the standard deviation and the histogram of these two options will reveal whether including temporal data makes a difference for our analyses.

It is important to note a couple of findings from the UW CAMP study. First, the guitar was correctly identified by CI users about 67% of the time while flute was identified the least at 31%[21]. The UW CAMP study also found that flute was most often confused with the cello, and interfamily confusion was the most common for woodwinds.

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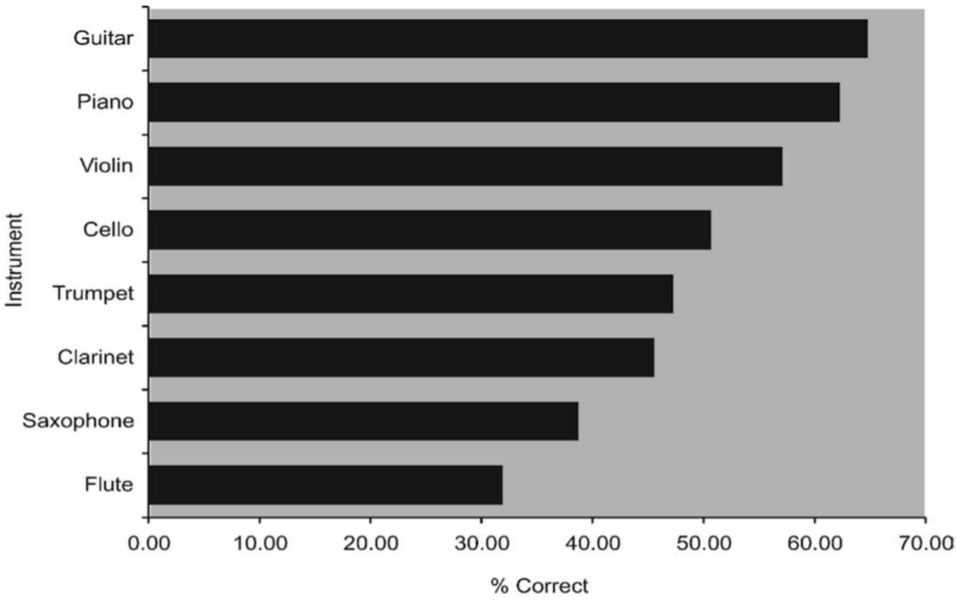


FIG. 3.
Graph showing the total percentage of correct responses scored by all listeners for each instrument, demonstrating relative difficulty of each instrument on the timbre test.

Figure 3.1 Performance of CI patients on Timbre recognition test from 2008 CAMP study *[21]*. Shows which instrument participnats were able to identify more correctly.

A cross correlogram will be used to quantify the similarities and differences in the electrodograms, with the hypothesis that highly correlated electrodograms would be less discriminable by CI users. Alternatively, a lower correlation would signify that a CI user would be better at distinguishing sounds.

The second objective is to determine the effect of two different coding strategies on the correlation of electrodograms. Two programs were created in BEPS+ to simulate different CI user settings. One program was called HiRes, which refers to a monopolar strategy that stimulates one electrode at a time. However, this strategy has been found to have broad electrical fields that contribute to poor perception of pitch[24], The other program is called Optima, which refers to a strategy that stimulates two neighboring electrodes at the same time at different ratios to provide improved spectral information[25]. Both programs implemented an 80 dB input dynamic range (IDR), which refers to the range of sounds captured for processing. The Most

Comfortable Loudness level (MCL), which is a psychophysical judgment of loudness measured in clinical units of electrical current called current units (cu)[26], was arbitrarily set to 150 and is a typical level for CI users of this device. Threshold Levels (TCL), the softest someone can hear, was set top 10% of the MCL, as typically done clinically. Both of these strategies process signals in a unique manner, ultimately attempting to retain, amplify, or manipulate the sound signal and therefore alter the way sample sounds are displayed within the electrodograms and provide insight as to which coding strategy might be better for music perception.

3.1.2 Electrodograms (ELs)

The following are examples of different instruments and notes displayed by the electrodograms with different signal processing strategies and matching spectrograms:

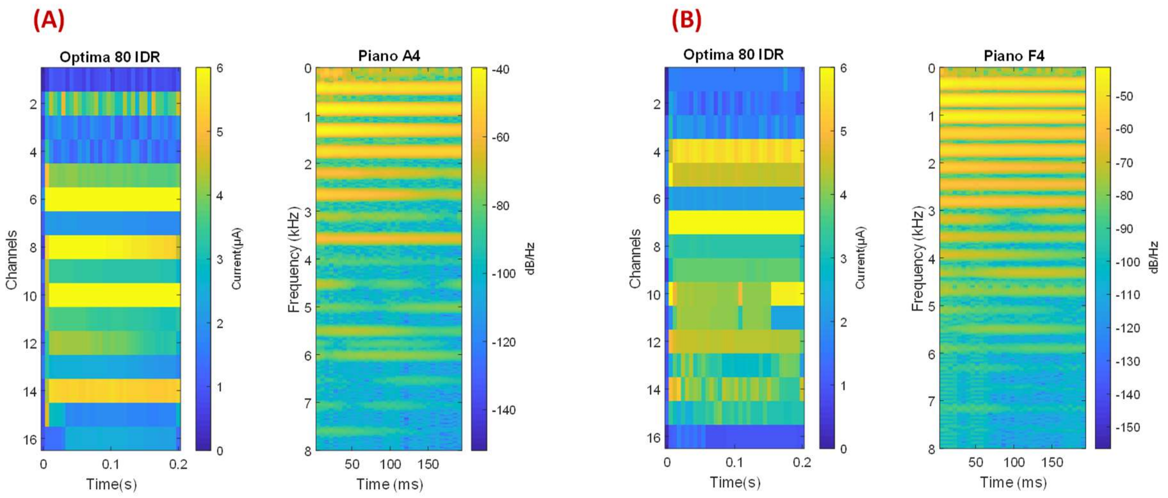


Figure 3.2:- Electrodogram (EL) of the CAMP study piano on notes A4 and F4. The signal processing strategy used was Optima at 80IDR. Each EL shows channels 1-16 on the cochler implant, channel 1 being closest to the apex of the cochlea and channel 16 being closer to the base of the cochlea. The higher channel numbers are stimulated by higher frequencies, while lower channels numbers are stimulated by lower frequecies. The intensity of the color in each of the channels represents the current in each channel. To the right of each EL is a spectrogram, limited to the range of frequencies processed by of a cochlear implant (approximately 100-8000Hz). The formants of the note can be seen as the repeating bands of high intensity, representing the fundamental frequenceis of the note.

From figure 3.2, it is clear that the electrodogram (EL) varies depending on the note that is played when the signal processing strategy and instrument are kept the same. The spectrogram to the right of each EL also shows how the frequency components change, which will in turn stimulate different channels of the CI. The more energy within the bandwidth of the electrode channel, the greater the intensity of current to the particular channel.

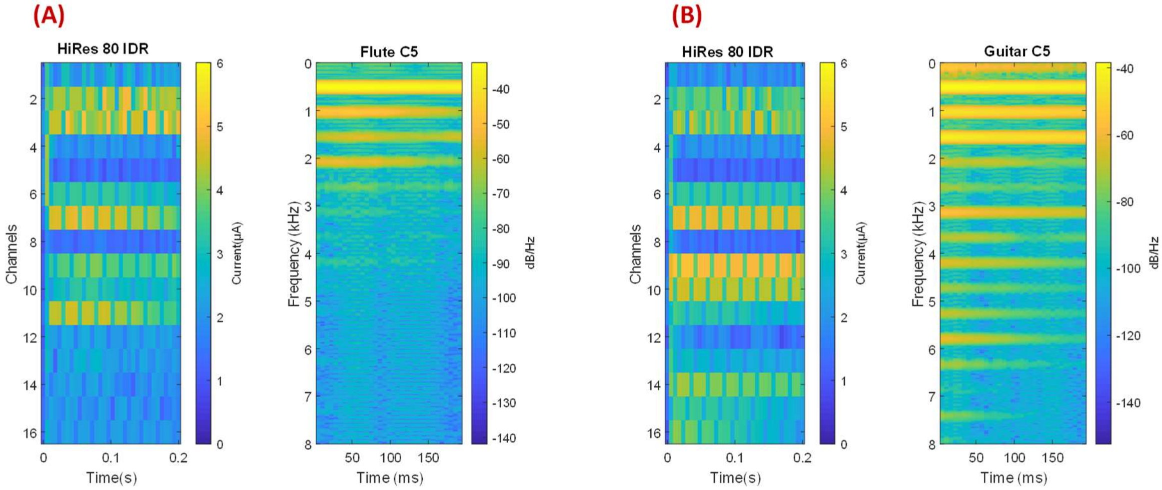


Figure 3.3- Electrodogram (EL) of the CAMP study flute on note C5 and guitar on C5. The signal processing strategy used was HiRes at 80IDR.

Figure 3.3 is an example of two different instruments on the EL with the same note and signal processing strategy. In this example, the spectrogram shows how many formants or fundamental frequencies were captured by the CI. The flute has much less frequency range because of the limitations of the CI. CIs have a frequency range of 0-8000Hz and will have difficulty interpreting sounds that have higher frequencies, such as the flute on C5. The spread of the frequencies is larger in the guitar, which results higher numbered channels closer to the base to be stimulated.

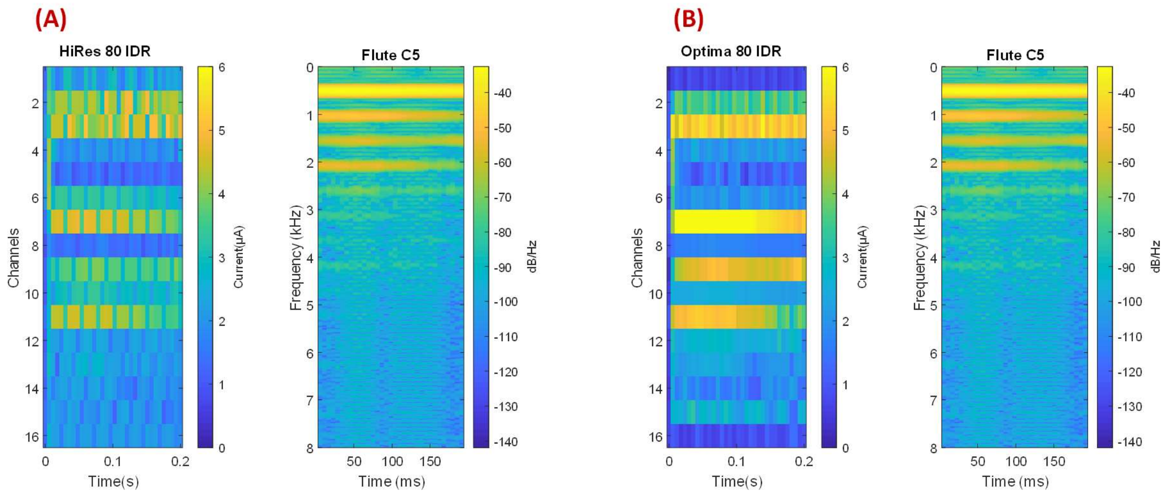


Figure 3.4- Electrodogram (EL) of the CAMP study flute C5. The figure shows the comparison between HiRes and Optima at 80IDR.

Figure 3.4 shows how the signal processing strategies vary on the same note and instrument. The current is much higher for Optima, which is probably due to the use of current steering that relies on adjacent electrodes for stimulation. Please view the Appendix Section 5.1 for all the ELs of each instrument used in this study.

The third objective of this project is to compare our electrodogram results with CI users' performance on the CAMP test and other potential samples of the same notes and instruments. Although the CAMP paradigm does offer some clarity on which instruments and notes patients were most successful at identifying or discriminating, it does not explicitly explain how the device is processing nor show if signal processing may be linked to the results. Thus, analyses of the samples with electrodograms may provide insight into why performance observed other than physiological explanations. Once again, quantifying the correlation between electrodograms for different instruments is one approach to estimate which instruments are most distinguishable from each other. There are three types of correlograms that will be helpful in accomplishing this:

1) The overall correlation between each instrument on a particular note 2) The correlation between notes within a particular instrument, 3) The correlation between instruments on a particular note, and 4) The correlation between multiple samples of the same notes and instruments (CAMP, Philharmonia, and Iowa). The overall correlation between each instrument in particular illuminates any confusion that may have occurred in the CAMP study (e.g. the flute and guitar or woodwind instruments) for comparison.

3.2 Results

3.2.1 Temporal vs. Average

Figure 3.5 shows the difference between averaging the current across each channel over time (x-axis in electrodogram) versus retaining the 120 element bins of temporal information for each channel. For both HiRes and Optima, the distributions are normal and look relatively similar. We wanted to know whether temporal information had an effect on our data. Overall, the distributions were relatively the same and would need to be furthered analyzed through a different method (e.g. changing the window size to include different tails and attacks of notes or duration of the signal). We therefore proceeded the rest of this study using the 120 element bins of temporal information for each channel.

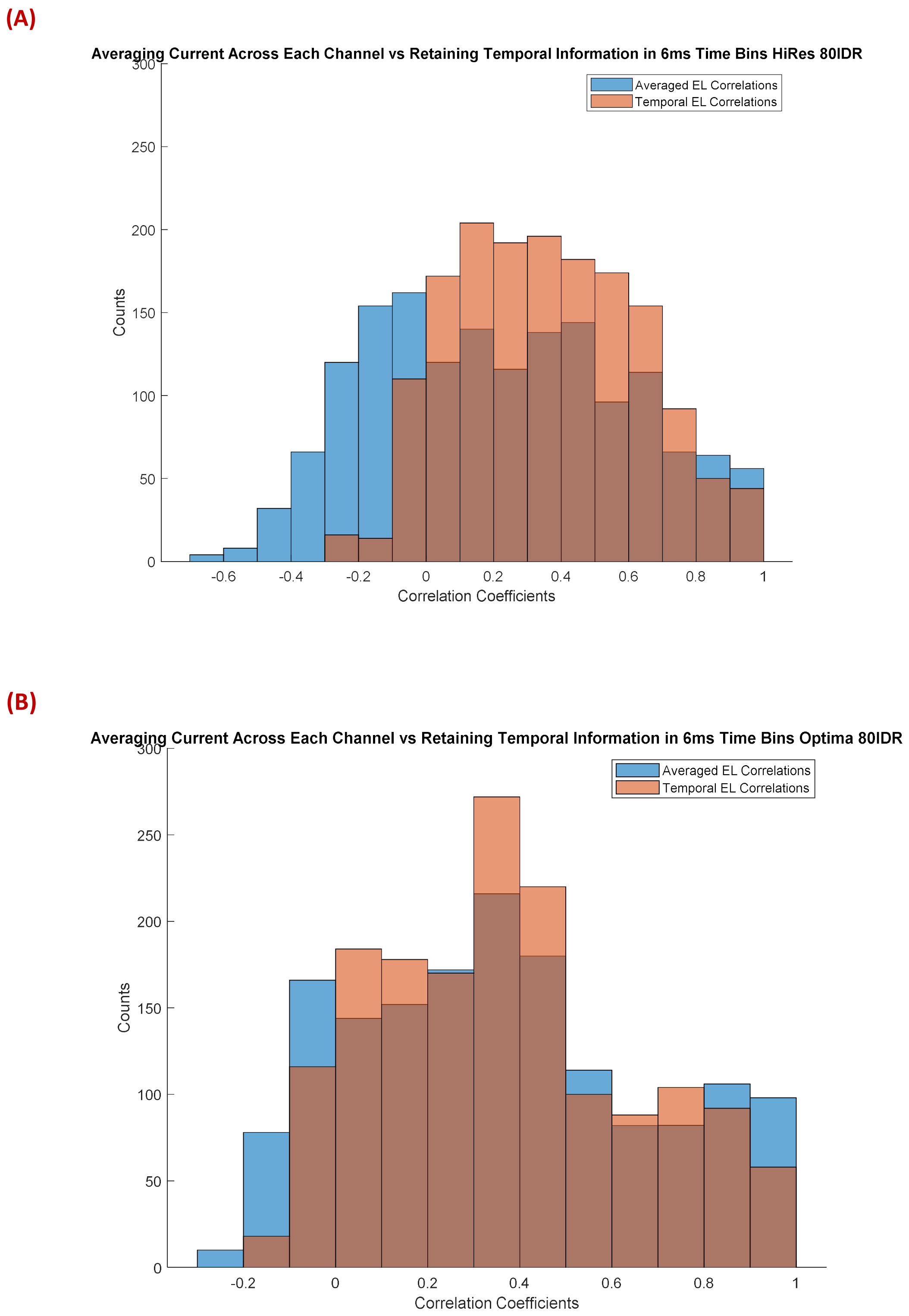
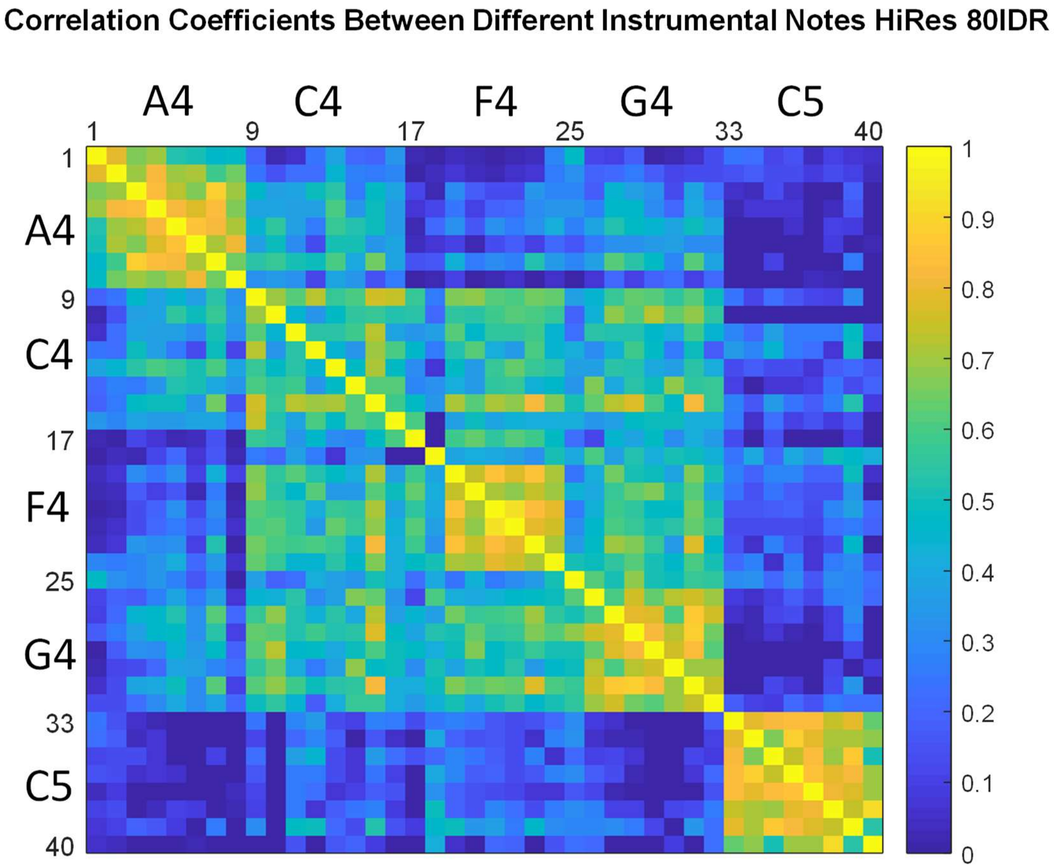


Figure 3.5 Distribution of correlations of both Averaged current of channels versus including temporal information within time bins of channels for **(A)** HiRes 80IDR and **(B)** Optima 80IDR. Both the means and standard deviation are included for the bar graphs.

3.2.2 Correlation Between All Notes and Instruments

(A)



(B)

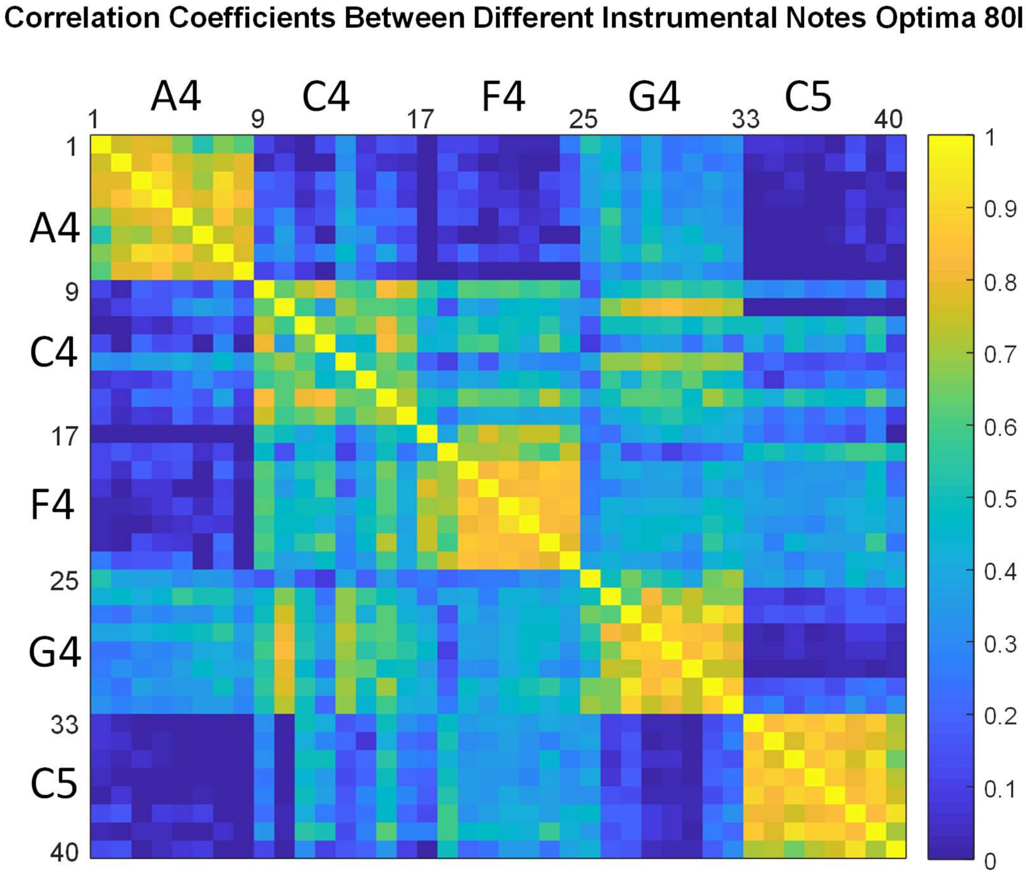
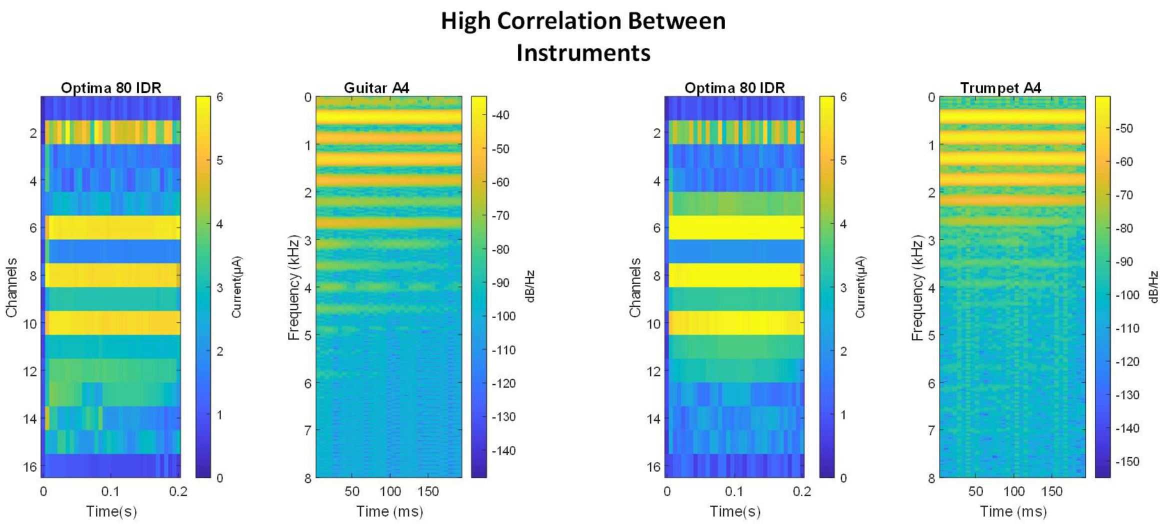


Figure 3.6 (Above)- Correlogram showing the correlation between each instrumental note. **(A)** Uses HiRes 80IDr for signal processing. **(B)** Uses Optima 80IDR for signal processing. For both (A) and (B) the instruments were grouped by notes. Going downward or across the graphs, the first numberings 1-8 are note A4, 9-16 are note C4, 17-24 are note F4, 25-32 are note G4, and 33-40 are note C5. The order of the instruments downward and across are in the following order and repeat for the successive note: cello, clarinet, flute, guitar, piano, saxophone, trumpet, and violin.

Figure 3.6 shows us the overall correlation of all the instruments on each note for both signal processing strategies. The grouping by notes into 8x8 squares (all 8 instruments on 1 note) can be seen showing relatively high correlations comparing different instruments on the same note. The proximity of the note also makes a difference, showing that the closer the note is to another, the higher the correlation. This is shown through groupings like A4 (numberings 1-8) and G4(numberings 25-32) which are only one whole step apart form each other. A4 and G4 is shown to much higher in correlation, and this pattern repeats itself for other relationships in close proximity of each other (e.g. F4 and G4).

3.2.3 Examples of High, Mid, and Low Correlations Between Instruments on EL and Spectrogram

The following graphs give a visual representation of what a low to high correlation would look like between instruments by keeping the notes the same. It is most important to notice the differences in current in each channel, as well as the number and intensity of formants in the spectrogram. The more distinct the EL and spectrogram appear form each other, the lower the correlation. The lower correlation, the more distinguishable the musical signals are likely to be from each other.


High Correlation Between Instruments

Optima 80 IDR

Guitar A4

Optima 80 IDR

Trumpet A4

Figure 3.7- ELs and Spectrograms comparing Guitar and Trumpet on A4. This is an example of musical signals that are highly correlated to each other.

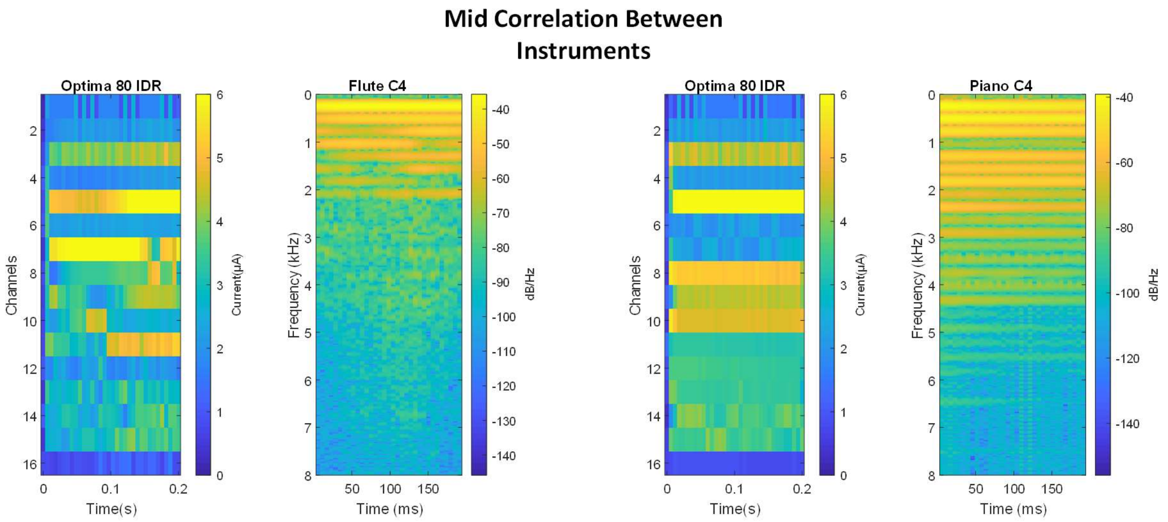


Figure 3.8- EL and Spectrogram comparing Flute and Piano on C4. This is an example of musical signals that are moderately correlated to each other.

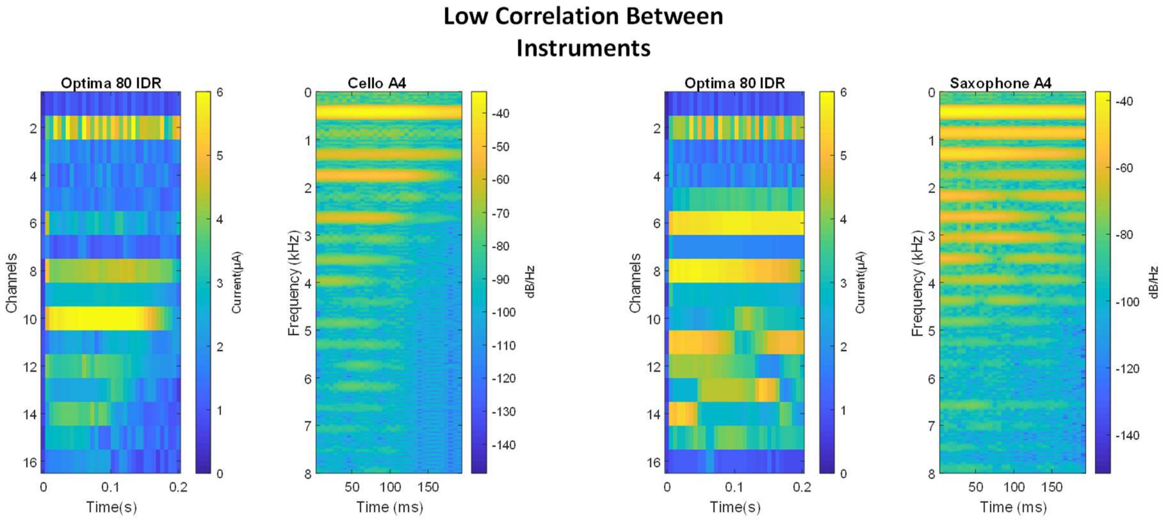


Figure 3.9- EL and Spectrogram comparing Cello and Saxophone on A4. This is an example of musical signals that are lowly correlated to each other.

3.2.4 Examples of High, Mid, and Low Correlations Between Notes on EL and Spectrogram

The following graphs give a visual representation of what a low to high correlation would look like between notes by keeping the instrument the same. The criteria of differences in the musical signal and low correlation apply as it did in the above figure.

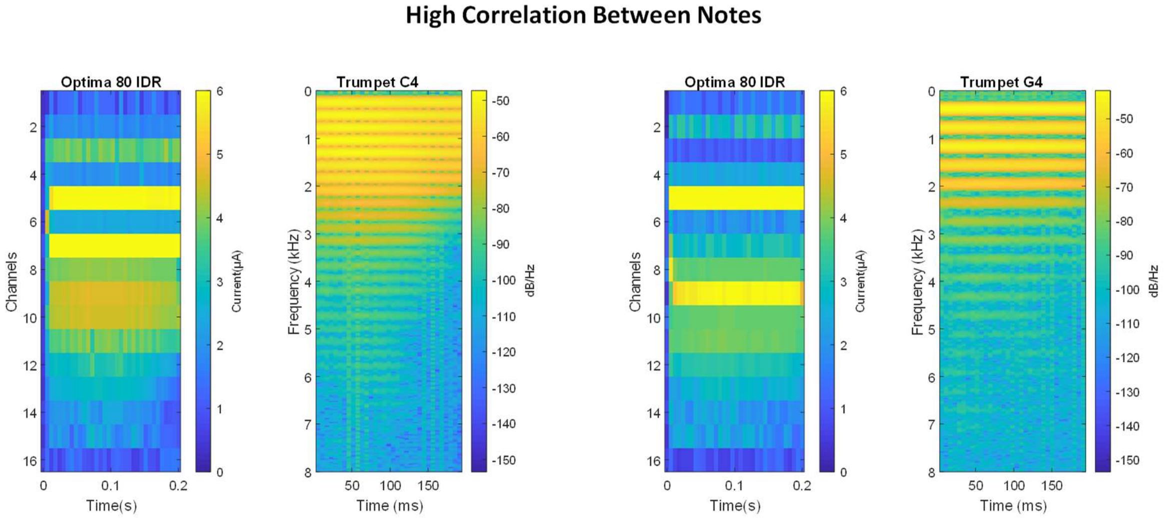


Figure 3.10- ELs and Spectrograms comparing C4 and A4 on Trumpet. This is an example of musical signals that are highly correlated to each other.

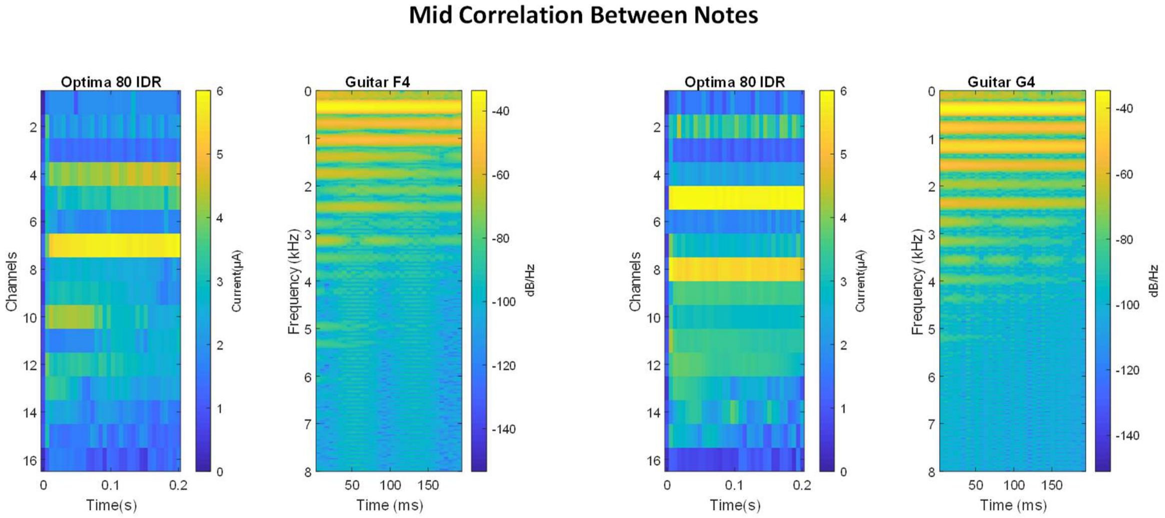


Figure 3.11- ELs and Spectrograms comparing F4 and G4 on Guitar. This is an example of musical signals that are moderately correlated to each other.

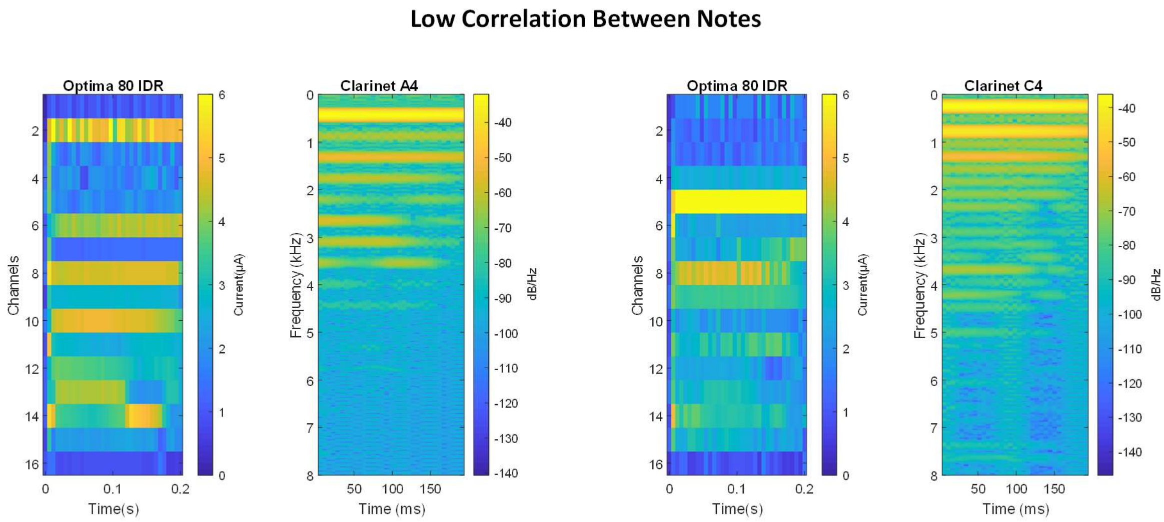
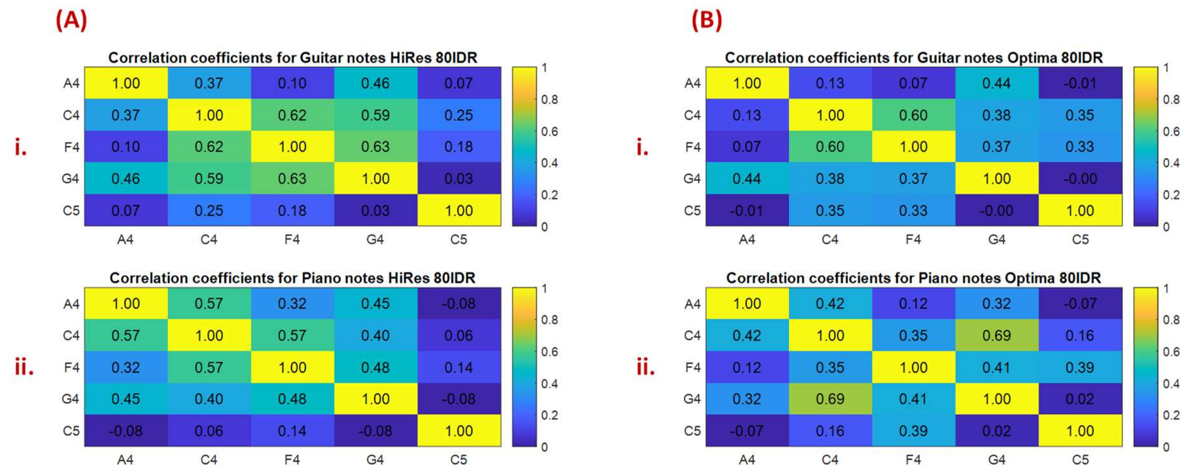


Figure 3.12- ELs and Spectrograms comparing A4 and C4 on Clarinet. This is an example of musical signals that are highly correlated to each other.

3.2.5 Correlation of Notes on Each Instrument



Correlation coefficients for Guitar notes HiRes 80IDR

	A4	C4	F4	G4	C5
A4	1.00	0.37	0.10	0.46	0.07
C4	0.37	1.00	0.62	0.59	0.25
F4	0.10	0.62	1.00	0.63	0.18
G4	0.46	0.59	0.63	1.00	0.03
C5	0.07	0.25	0.18	0.03	1.00

Correlation coefficients for Guitar notes Optima 80IDR

	A4	C4	F4	G4	C5
A4	1.00	0.13	0.07	0.44	-0.01
C4	0.13	1.00	0.60	0.38	0.35
F4	0.07	0.60	1.00	0.37	0.33
G4	0.44	0.38	0.37	1.00	-0.00
C5	-0.01	0.35	0.33	-0.00	1.00

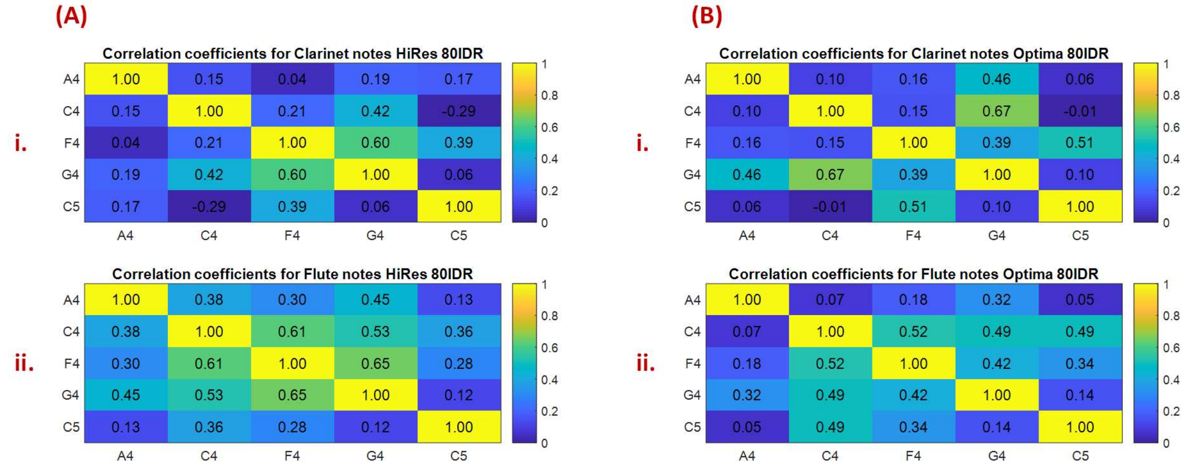
Correlation coefficients for Piano notes HiRes 80IDR

	A4	C4	F4	G4	C5
A4	1.00	0.57	0.32	0.45	-0.08
C4	0.57	1.00	0.57	0.40	0.06
F4	0.32	0.57	1.00	0.48	0.14
G4	0.45	0.40	0.48	1.00	-0.08
C5	-0.08	0.06	0.14	-0.08	1.00

Correlation coefficients for Piano notes Optima 80IDR

	A4	C4	F4	G4	C5
A4	1.00	0.42	0.12	0.32	-0.07
C4	0.42	1.00	0.35	0.69	0.16
F4	0.12	0.35	1.00	0.41	0.39
G4	0.32	0.69	0.41	1.00	0.02
C5	-0.07	0.16	0.39	0.02	1.00

Figure 3.13 Correlation between notes on CAMP study guitar (strings) and piano (pitched percussion). **(A)** Uses HiRes 80IDR (**B)** Uses Optima 80IDR. Correlation is shown on a scale from 0 to 1; the greater the correlation the less distinguishable the note, the lower the correlation, the more distinguishable.



Correlation coefficients for Clarinet notes HiRes 80IDR

	A4	C4	F4	G4	C5
A4	1.00	0.15	0.04	0.19	0.17
C4	0.15	1.00	0.21	0.42	-0.29
F4	0.04	0.21	1.00	0.60	0.39
G4	0.19	0.42	0.60	1.00	0.06
C5	0.17	-0.29	0.39	0.06	1.00

Correlation coefficients for Clarinet notes Optima 80IDR

	A4	C4	F4	G4	C5
A4	1.00	0.10	0.16	0.46	0.06
C4	0.10	1.00	0.15	0.67	-0.01
F4	0.16	0.15	1.00	0.39	0.51
G4	0.46	0.67	0.39	1.00	0.10
C5	0.06	-0.01	0.51	0.10	1.00

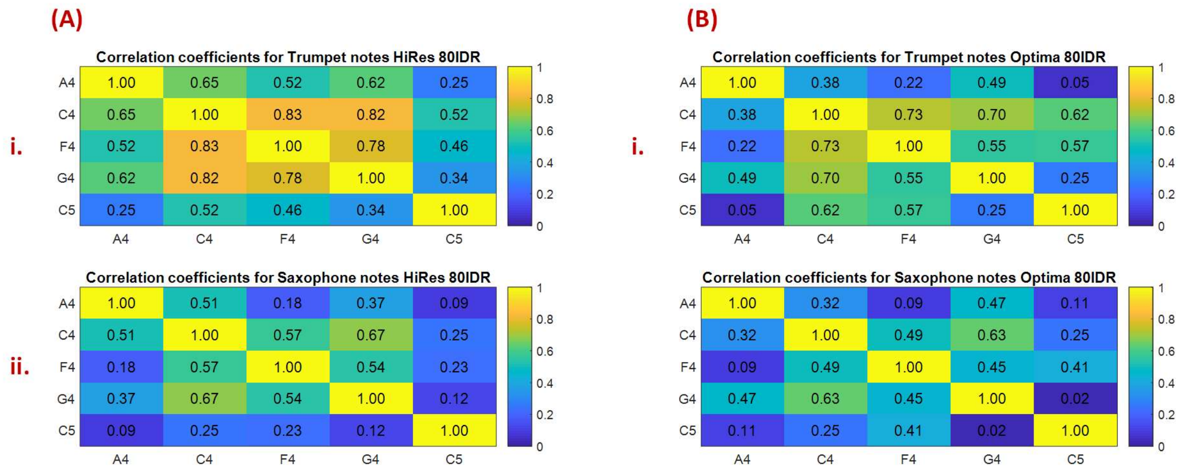
Correlation coefficients for Flute notes HiRes 80IDR

	A4	C4	F4	G4	C5
A4	1.00	0.38	0.30	0.45	0.13
C4	0.38	1.00	0.61	0.53	0.36
F4	0.30	0.61	1.00	0.65	0.28
G4	0.45	0.53	0.65	1.00	0.12
C5	0.13	0.36	0.28	0.12	1.00

Correlation coefficients for Flute notes Optima 80IDR

	A4	C4	F4	G4	C5
A4	1.00	0.07	0.18	0.32	0.05
C4	0.07	1.00	0.52	0.49	0.49
F4	0.18	0.52	1.00	0.42	0.34
G4	0.32	0.49	0.42	1.00	0.14
C5	0.05	0.49	0.34	0.14	1.00

Figure 3.14- Correlation between notes on Camp study woodwinds: clarinet and flute. **(A)** Uses HiRes 80IDR (**B)** Uses Optima 80IDR.



Correlation coefficients for Trumpet notes HiRes 80IDR

	A4	C4	F4	G4	C5
A4	1.00	0.65	0.52	0.62	0.25
C4	0.65	1.00	0.83	0.82	0.52
F4	0.52	0.83	1.00	0.78	0.46
G4	0.62	0.82	0.78	1.00	0.34
C5	0.25	0.52	0.46	0.34	1.00

Correlation coefficients for Trumpet notes Optima 80IDR

	A4	C4	F4	G4	C5
A4	1.00	0.38	0.22	0.49	0.05
C4	0.38	1.00	0.73	0.70	0.62
F4	0.22	0.73	1.00	0.55	0.57
G4	0.49	0.70	0.55	1.00	0.25
C5	0.05	0.62	0.57	0.25	1.00

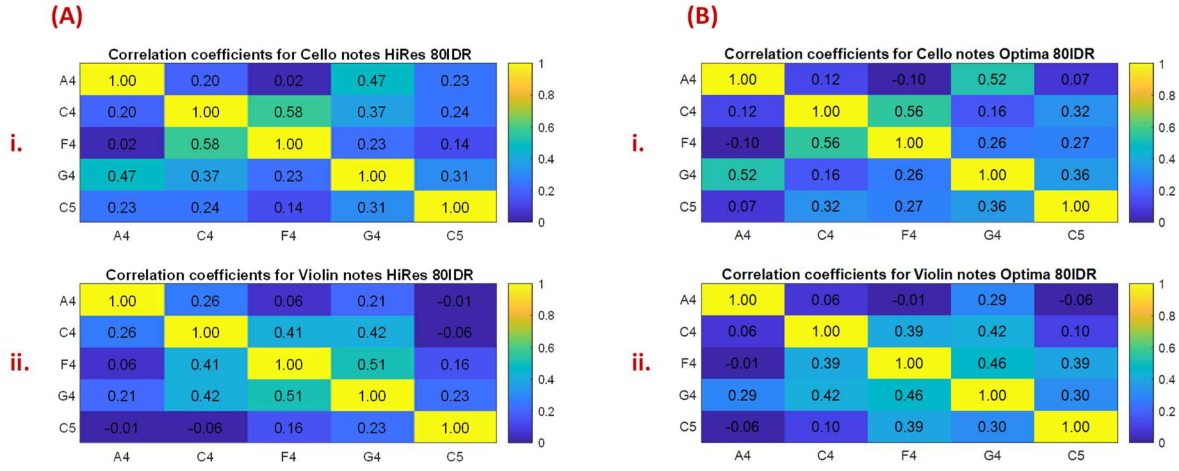
Correlation coefficients for Saxophone notes HiRes 80IDR

	A4	C4	F4	G4	C5
A4	1.00	0.51	0.18	0.37	0.09
C4	0.51	1.00	0.57	0.67	0.25
F4	0.18	0.57	1.00	0.54	0.23
G4	0.37	0.67	0.54	1.00	0.12
C5	0.09	0.25	0.23	0.12	1.00

Correlation coefficients for Saxophone notes Optima 80IDR

	A4	C4	F4	G4	C5
A4	1.00	0.32	0.09	0.47	0.11
C4	0.32	1.00	0.49	0.63	0.25
F4	0.09	0.49	1.00	0.45	0.41
G4	0.47	0.63	0.45	1.00	0.02
C5	0.11	0.25	0.41	0.02	1.00

Figure 3.15 Correlation between notes on Camp study Trumpet (brass) and Saxophone(woodwind). **(A)** Uses HiRes 80IDR (**B)** Uses Optima 80IDR.



Correlation coefficients for Cello notes HiRes 80IDR

	A4	C4	F4	G4	C5
A4	1.00	0.20	0.02	0.47	0.23
C4	0.20	1.00	0.58	0.37	0.24
F4	0.02	0.58	1.00	0.23	0.14
G4	0.47	0.37	0.23	1.00	0.31
C5	0.23	0.24	0.14	0.31	1.00

Correlation coefficients for Cello notes Optima 80IDR

	A4	C4	F4	G4	C5
A4	1.00	0.12	-0.10	0.52	0.07
C4	0.12	1.00	0.56	0.16	0.32
F4	-0.10	0.56	1.00	0.26	0.27
G4	0.52	0.16	0.26	1.00	0.36
C5	0.07	0.32	0.27	0.36	1.00

Correlation coefficients for Violin notes HiRes 80IDR

	A4	C4	F4	G4	C5
A4	1.00	0.26	0.06	0.21	-0.01
C4	0.26	1.00	0.41	0.42	-0.06
F4	0.06	0.41	1.00	0.51	0.16
G4	0.21	0.42	0.51	1.00	0.23
C5	-0.01	-0.06	0.16	0.23	1.00

Correlation coefficients for Violin notes Optima 80IDR

	A4	C4	F4	G4	C5
A4	1.00	0.06	-0.01	0.29	-0.06
C4	0.06	1.00	0.39	0.42	0.10
F4	-0.01	0.39	1.00	0.46	0.39
G4	0.29	0.42	0.46	1.00	0.30
C5	-0.06	0.10	0.39	0.30	1.00

Figure 3.16- Correlation between notes on Camp study strings: cello and violin. **(A)** Uses HiRes 80IDR (**B)** Uses Optima 80IDR.

3.2.6 HiRes vs Optima Instruments

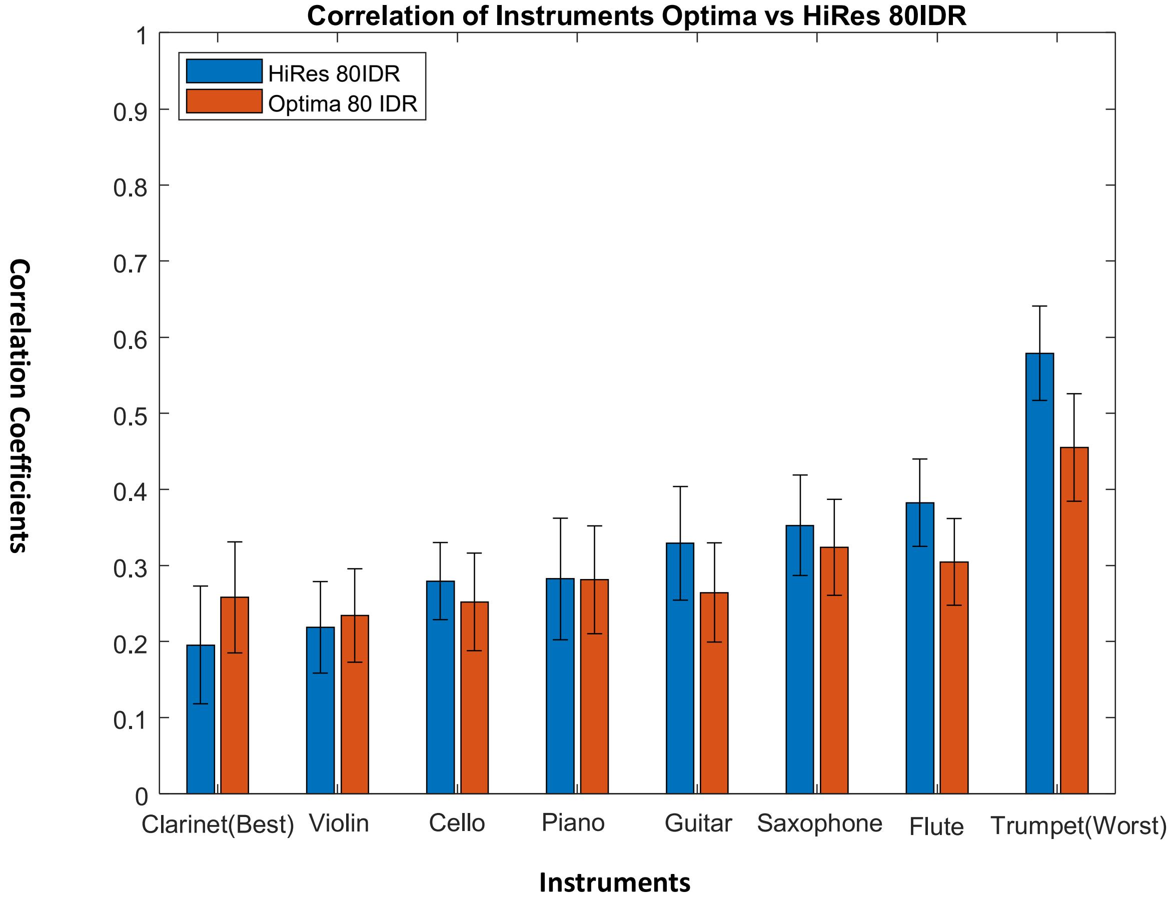


Figure 3.17 The comparison between correlations from the notes within each of the 8 instruments from the CAMP study on two signal processing strategies. To reiterate, a lower correlation represent an instrument that is more distinguishable from another and vice versa.

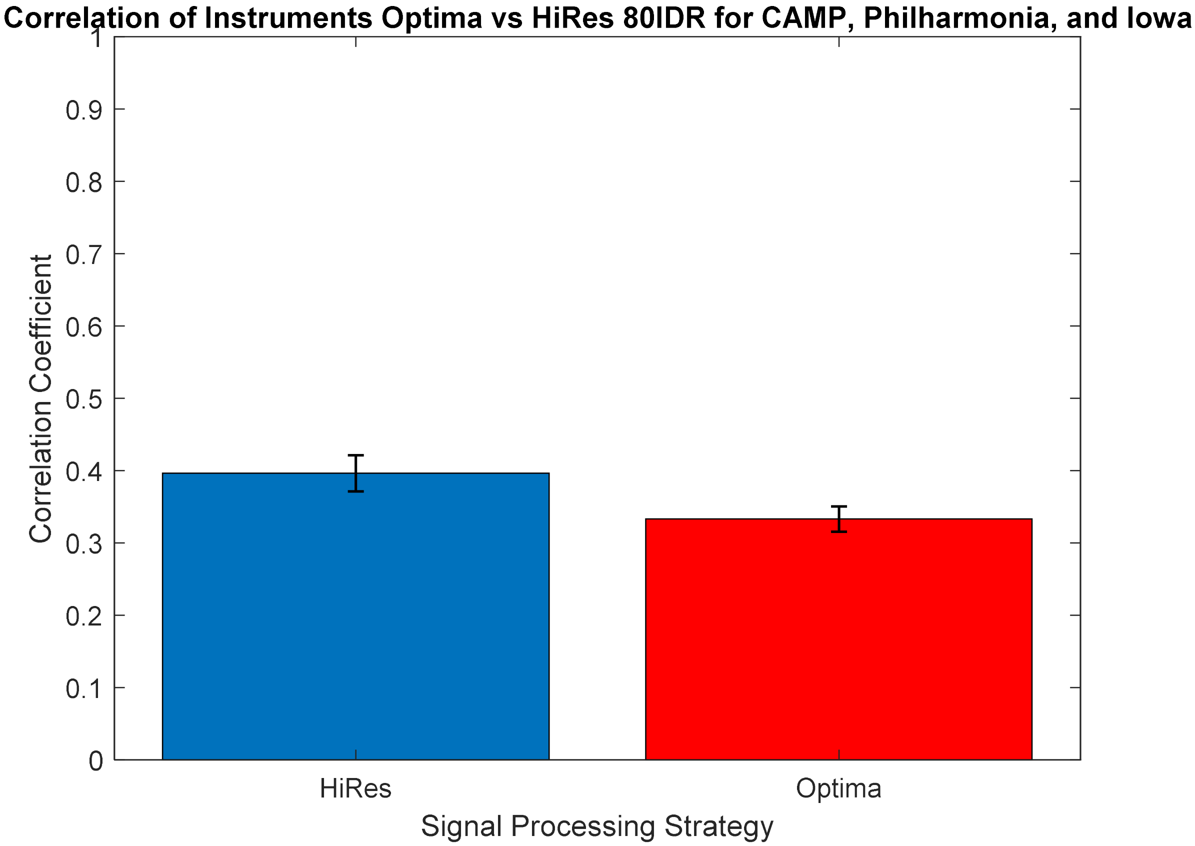
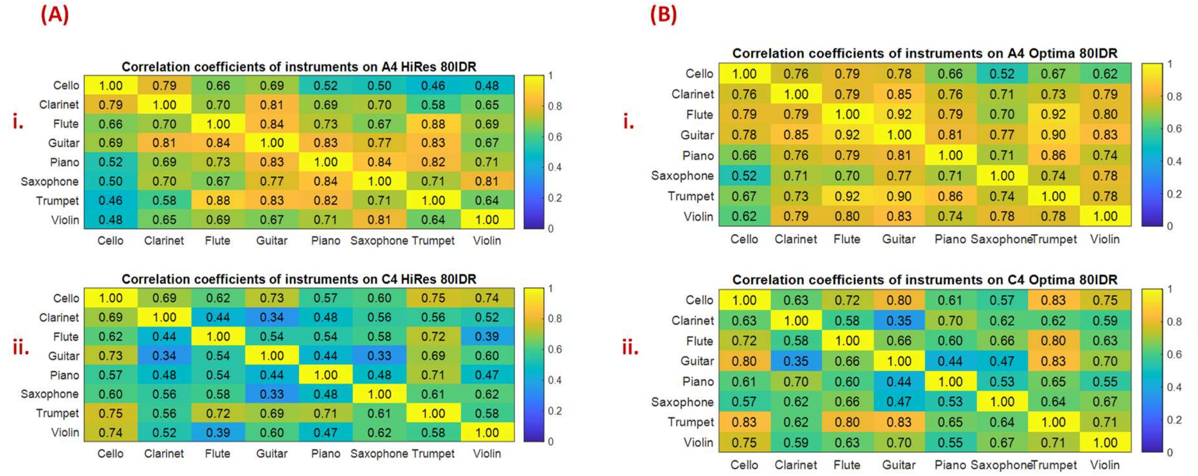


Figure 3.18- Comparing Correlation of instruments on HiRes 80IDR versus Optima 80IDR.

Notably for the CAMP samples, for HiRes the clarinet had the lowest correlation at 0.20 and the trumpet the highest correlation at 0.58. For Optima, the violin had the lowest correlation at 0.26 and the trumpet had the highest correlation at 0.45. In addition to comparing correlations of instruments for the CAMP study, samples from CAMP, Philharmonia, and Iowa were combined to create two sample comparing HiRes and Optima for the 8 different instruments (n=24). A two sample two tailed test assuming unequal variance was used with an alpha level of 0.05. The p-value comparing HiRes and Optima on the multiple samples of the instruments was p=0.0190.

3.2.7 Correlation of Instruments on Each Note

These graphs are equivalent to zooming in on the diagonal 8x8 squares in Figure 3.6 for both Hires and Optima 80IDR.



Correlation coefficients of instruments on A4 HiRes 80IDR

	Cello	Clarinet	Flute	Guitar	Piano	Saxophone	Trumpet	Violin
Cello	1.00	0.79	0.66	0.69	0.52	0.50	0.46	0.48
Clarinet	0.79	1.00	0.70	0.81	0.69	0.70	0.58	0.65
Flute	0.66	0.70	1.00	0.84	0.73	0.67	0.88	0.69
Guitar	0.69	0.81	0.84	1.00	0.83	0.77	0.83	0.67
Piano	0.52	0.69	0.73	0.83	1.00	0.84	0.82	0.71
Saxophone	0.50	0.70	0.67	0.77	0.84	1.00	0.71	0.81
Trumpet	0.46	0.58	0.88	0.83	0.82	0.71	1.00	0.64
Violin	0.48	0.65	0.69	0.67	0.71	0.81	0.64	1.00

Correlation coefficients of instruments on A4 Optima 80IDR

	Cello	Clarinet	Flute	Guitar	Piano	Saxophone	Trumpet	Violin
Cello	1.00	0.76	0.79	0.78	0.66	0.52	0.67	0.62
Clarinet	0.76	1.00	0.79	0.85	0.76	0.71	0.73	0.79
Flute	0.79	0.79	1.00	0.92	0.79	0.70	0.92	0.80
Guitar	0.78	0.85	0.92	1.00	0.81	0.77	0.90	0.83
Piano	0.66	0.76	0.79	0.81	1.00	0.71	0.86	0.74
Saxophone	0.52	0.71	0.70	0.77	0.71	1.00	0.74	0.78
Trumpet	0.67	0.73	0.92	0.90	0.86	0.74	1.00	0.78
Violin	0.62	0.79	0.80	0.83	0.74	0.78	0.78	1.00

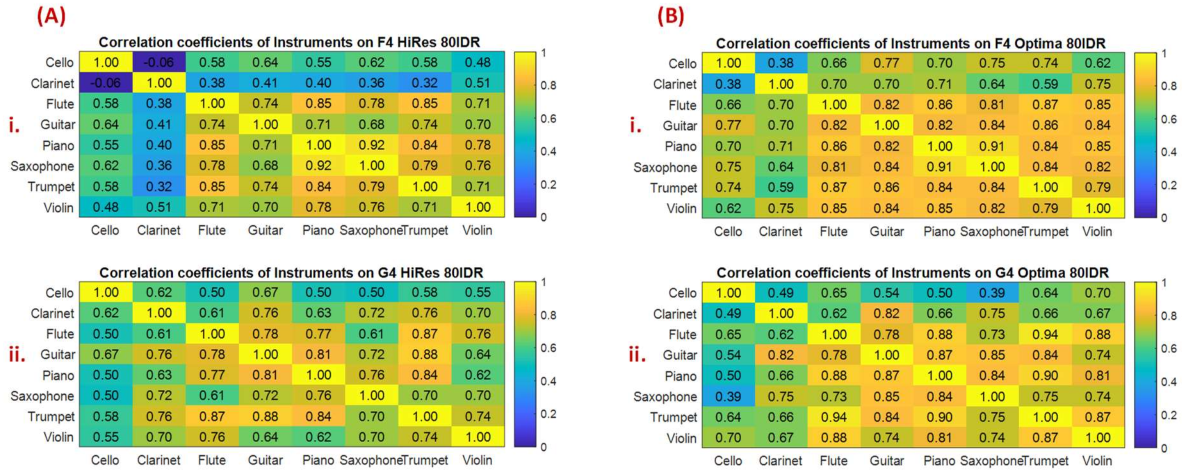
Correlation coefficients of instruments on C4 HiRes 80IDR

	Cello	Clarinet	Flute	Guitar	Piano	Saxophone	Trumpet	Violin
Cello	1.00	0.69	0.62	0.73	0.57	0.60	0.75	0.74
Clarinet	0.69	1.00	0.44	0.34	0.48	0.56	0.56	0.52
Flute	0.62	0.44	1.00	0.54	0.54	0.58	0.72	0.39
Guitar	0.73	0.34	0.54	1.00	0.44	0.33	0.69	0.60
Piano	0.57	0.48	0.54	0.44	1.00	0.48	0.71	0.47
Saxophone	0.60	0.56	0.58	0.33	0.48	1.00	0.61	0.62
Trumpet	0.75	0.56	0.72	0.69	0.71	0.61	1.00	0.58
Violin	0.74	0.52	0.39	0.60	0.47	0.62	0.58	1.00

Correlation coefficients of instruments on C4 Optima 80IDR

	Cello	Clarinet	Flute	Guitar	Piano	Saxophone	Trumpet	Violin
Cello	1.00	0.63	0.72	0.80	0.61	0.57	0.83	0.75
Clarinet	0.63	1.00	0.58	0.35	0.70	0.62	0.62	0.59
Flute	0.72	0.58	1.00	0.66	0.60	0.66	0.80	0.63
Guitar	0.80	0.35	0.66	1.00	0.44	0.47	0.83	0.70
Piano	0.61	0.70	0.60	0.44	1.00	0.53	0.65	0.55
Saxophone	0.57	0.62	0.66	0.47	0.53	1.00	0.64	0.67
Trumpet	0.83	0.62	0.80	0.83	0.65	0.64	1.00	0.71
Violin	0.75	0.59	0.63	0.70	0.55	0.67	0.71	1.00

Figure 3.19 Correlation comparing the instruments on notes **(i)** A4 and **(ii)** C4. Correlation is also shown on a scale from 0 to 1, representing a higher distinguisability of an instrument the lower the correlation. **(A)** was conducted on HiRes and **(B)** on Optima.



Correlation coefficients of Instruments on F4 HiRes 80IDR

	Cello	Clarinet	Flute	Guitar	Piano	Saxophone	Trumpet	Violin
Cello	1.00	-0.06	0.58	0.64	0.55	0.62	0.58	0.48
Clarinet	-0.06	1.00	0.38	0.41	0.40	0.36	0.32	0.51
Flute	0.58	0.38	1.00	0.74	0.85	0.78	0.85	0.71
Guitar	0.64	0.41	0.74	1.00	0.71	0.68	0.74	0.70
Piano	0.55	0.40	0.85	0.71	1.00	0.92	0.84	0.78
Saxophone	0.62	0.36	0.78	0.68	0.92	1.00	0.79	0.76
Trumpet	0.58	0.32	0.85	0.74	0.84	0.79	1.00	0.71
Violin	0.48	0.51	0.71	0.70	0.78	0.76	0.71	1.00

Correlation coefficients of Instruments on F4 Optima 80IDR

	Cello	Clarinet	Flute	Guitar	Piano	Saxophone	Trumpet	Violin
Cello	1.00	0.38	0.66	0.77	0.70	0.75	0.74	0.62
Clarinet	0.38	1.00	0.70	0.70	0.71	0.64	0.59	0.75
Flute	0.66	0.70	1.00	0.82	0.86	0.81	0.87	0.85
Guitar	0.77	0.70	0.82	1.00	0.82	0.84	0.86	0.84
Piano	0.70	0.71	0.86	0.82	1.00	0.91	0.84	0.85
Saxophone	0.75	0.64	0.81	0.84	0.91	1.00	0.84	0.82
Trumpet	0.74	0.59	0.87	0.86	0.84	0.84	1.00	0.79
Violin	0.62	0.75	0.85	0.84	0.85	0.82	0.79	1.00

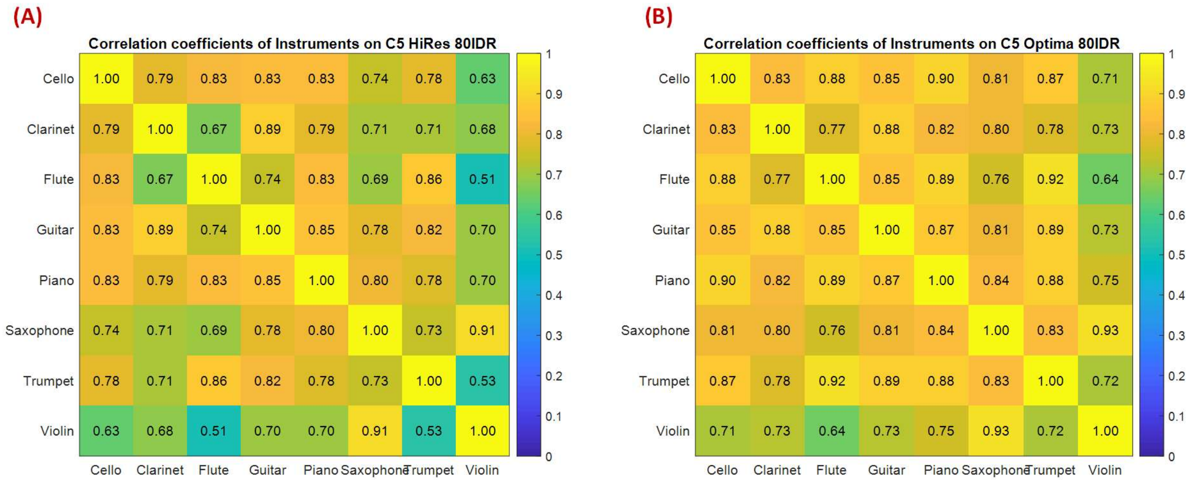
Correlation coefficients of Instruments on G4 HiRes 80IDR

	Cello	Clarinet	Flute	Guitar	Piano	Saxophone	Trumpet	Violin
Cello	1.00	0.62	0.50	0.67	0.50	0.50	0.58	0.55
Clarinet	0.62	1.00	0.61	0.76	0.63	0.72	0.76	0.70
Flute	0.50	0.61	1.00	0.78	0.77	0.61	0.87	0.76
Guitar	0.67	0.76	0.78	1.00	0.81	0.72	0.88	0.64
Piano	0.50	0.63	0.77	0.81	1.00	0.76	0.84	0.62
Saxophone	0.50	0.72	0.61	0.72	0.76	1.00	0.70	0.70
Trumpet	0.58	0.76	0.87	0.88	0.84	0.70	1.00	0.74
Violin	0.55	0.70	0.76	0.64	0.62	0.70	0.74	1.00

Correlation coefficients of Instruments on G4 Optima 80IDR

	Cello	Clarinet	Flute	Guitar	Piano	Saxophone	Trumpet	Violin
Cello	1.00	0.49	0.65	0.54	0.50	0.39	0.64	0.70
Clarinet	0.49	1.00	0.62	0.82	0.66	0.75	0.66	0.67
Flute	0.65	0.62	1.00	0.78	0.88	0.73	0.94	0.88
Guitar	0.54	0.82	0.78	1.00	0.87	0.85	0.84	0.74
Piano	0.50	0.66	0.88	0.87	1.00	0.84	0.90	0.81
Saxophone	0.39	0.75	0.73	0.85	0.84	1.00	0.75	0.74
Trumpet	0.64	0.66	0.94	0.84	0.90	0.75	1.00	0.87
Violin	0.70	0.67	0.88	0.74	0.81	0.74	0.87	1.00

Figure 3.20 Correlation comparing the instruments on notes **(i)** F4 and **(ii)** G4**. (A)** was conducted on HiRes and **(B)** on Optima.



Correlation coefficients of Instruments on C5 HiRes 80IDR

	Cello	Clarinet	Flute	Guitar	Piano	Saxophone	Trumpet	Violin
Cello	1.00	0.79	0.83	0.83	0.83	0.74	0.78	0.63
Clarinet	0.79	1.00	0.67	0.89	0.79	0.71	0.71	0.68
Flute	0.83	0.67	1.00	0.74	0.83	0.69	0.86	0.51
Guitar	0.83	0.89	0.74	1.00	0.85	0.78	0.82	0.70
Piano	0.83	0.79	0.83	0.85	1.00	0.80	0.78	0.70
Saxophone	0.74	0.71	0.69	0.78	0.80	1.00	0.73	0.91
Trumpet	0.78	0.71	0.86	0.82	0.78	0.73	1.00	0.53
Violin	0.63	0.68	0.51	0.70	0.70	0.91	0.53	1.00

Correlation coefficients of Instruments on C5 Optima 80IDR

	Cello	Clarinet	Flute	Guitar	Piano	Saxophone	Trumpet	Violin
Cello	1.00	0.83	0.88	0.85	0.90	0.81	0.87	0.71
Clarinet	0.83	1.00	0.77	0.88	0.82	0.80	0.78	0.73
Flute	0.88	0.77	1.00	0.85	0.89	0.76	0.92	0.64
Guitar	0.85	0.88	0.85	1.00	0.87	0.81	0.89	0.73
Piano	0.90	0.82	0.89	0.87	1.00	0.84	0.88	0.75
Saxophone	0.81	0.80	0.76	0.81	0.84	1.00	0.83	0.93
Trumpet	0.87	0.78	0.92	0.89	0.88	0.83	1.00	0.72
Violin	0.71	0.73	0.64	0.73	0.75	0.93	0.72	1.00

Figure 3.21 Correlation comparing the instruments on notes C5 **(A)** conducted on HiRes and **(B)** on Optima.

3.2.8 HiRes vs Optima Notes

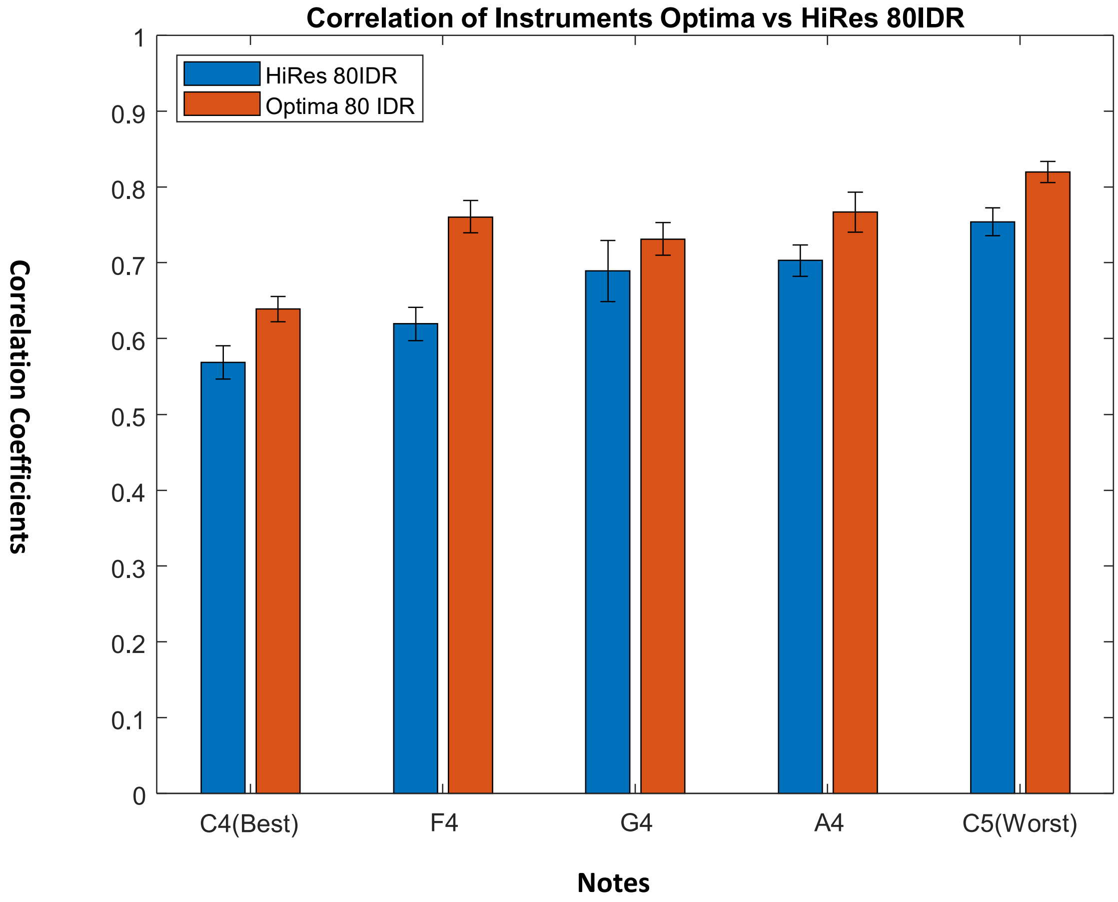


Figure 3.22 The comparison between the eight instruments on each signal processing strategy for the CAMP study. To reiterate, a lower correlation represent a note that is more distinguishable and vice versa.

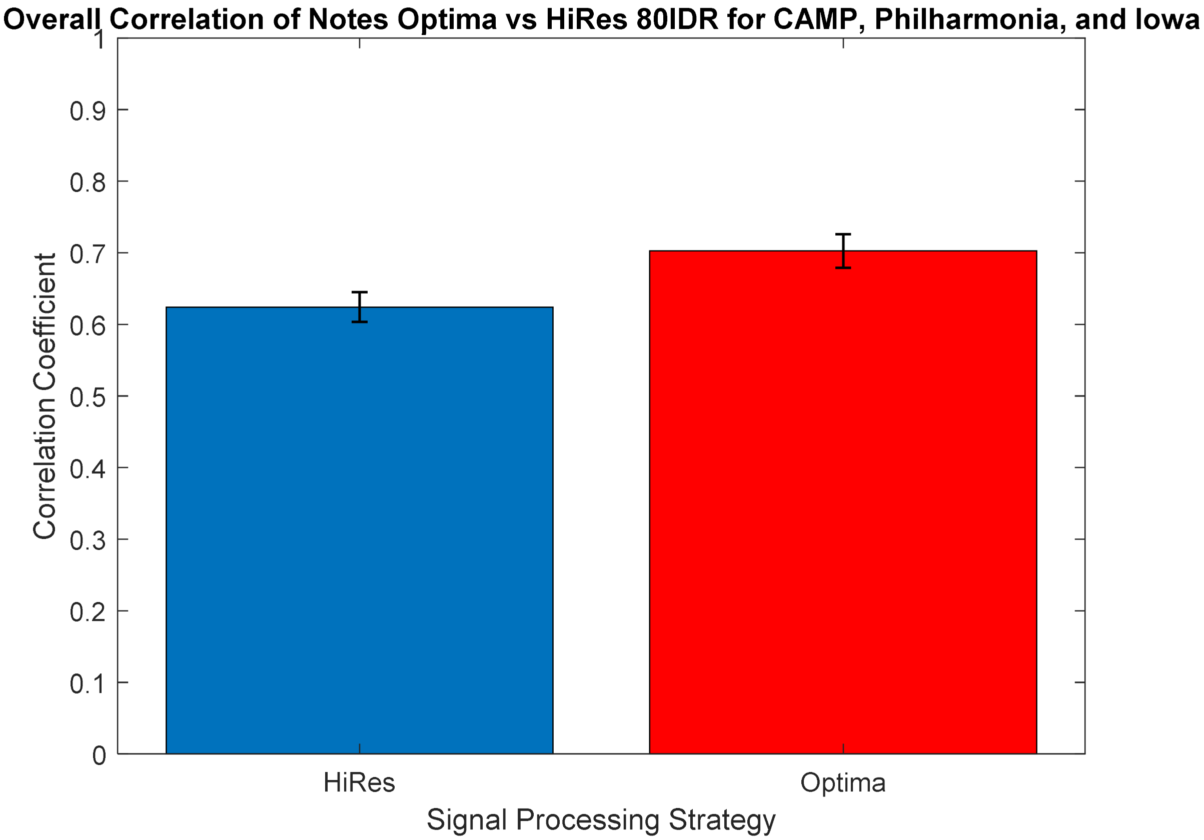
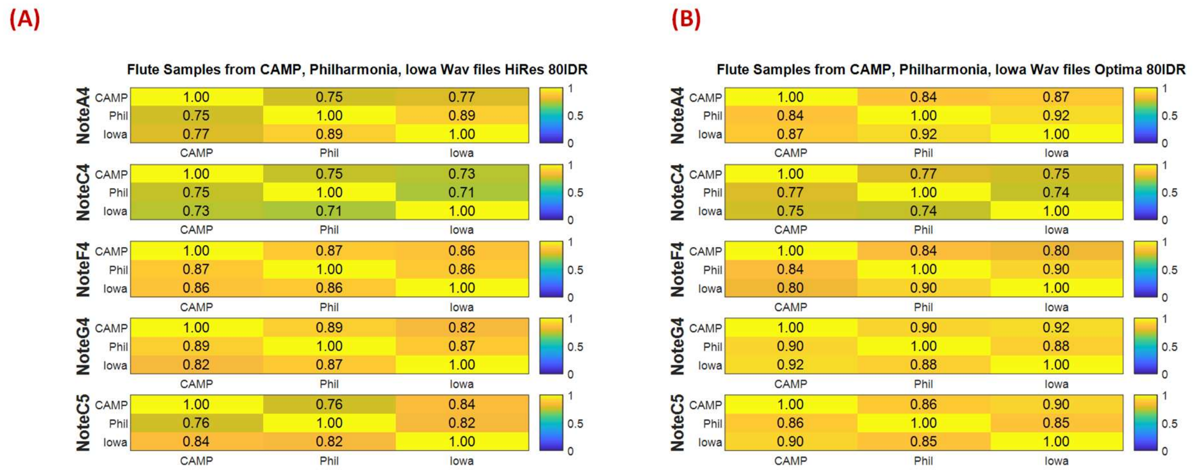


Figure 3.23- Comparing Correlation of notes on HiRes 80IDR versus Optima 80IDR.

Notably for the CAMP samples, for HiRes C4 had the lowest correlation at 0.63 and C5 had the highest correlation at 0.81. For Optima, C4 again had the lowest correlation at 0.56 and C5 also had the highest correlation at 0.75. Additionally, samples from CAMP, Philharmonia, and Iowa were combined to create two sample comparing HiRes and Optima for the 5 different notes (n=15). A two sample two tailed t-test assuming unequal variance was used with an alpha level of 0.05. The p-value comparing HiRes and Optima on the multiple samples of the notes was p=0.0445.

3.2.9 CAMP vs Philharmonia vs Iowa

The following graphs show how each of the instruments and notes compare with each other from different samples. Please see the Appendix Section 5.2 for the rest of the correlograms, the following graphs give an idea of how different samples can compare against each other in different instrument groups.



(A) Flute Samples from CAMP, Philharmonia, Iowa Wav files HiRes 80IDR

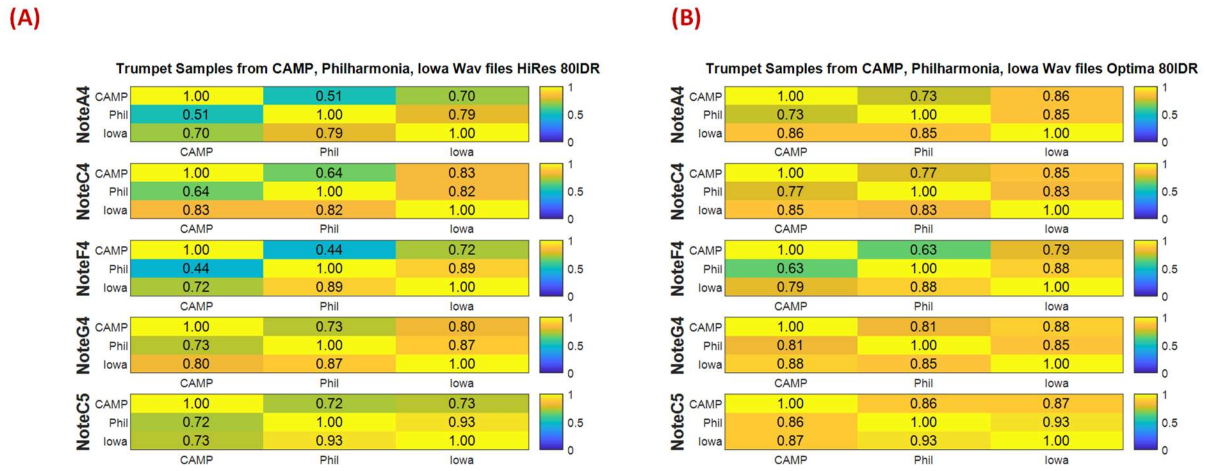
		CAMP	Phil	Iowa
NoteA4	CAMP	1.00	0.75	0.77
	Phil	0.75	1.00	0.89
	Iowa	0.77	0.89	1.00
NoteC4	CAMP	1.00	0.75	0.73
	Phil	0.75	1.00	0.71
	Iowa	0.73	0.71	1.00
NoteF4	CAMP	1.00	0.87	0.86
	Phil	0.87	1.00	0.86
	Iowa	0.86	0.86	1.00
NoteG4	CAMP	1.00	0.89	0.82
	Phil	0.89	1.00	0.87
	Iowa	0.82	0.87	1.00
NoteC5	CAMP	1.00	0.76	0.84
	Phil	0.76	1.00	0.82
	Iowa	0.84	0.82	1.00

(B) Flute Samples from CAMP, Philharmonia, Iowa Wav files Optima 80IDR

		CAMP	Phil	Iowa
NoteA4	CAMP	1.00	0.84	0.87
	Phil	0.84	1.00	0.92
	Iowa	0.87	0.92	1.00
NoteC4	CAMP	1.00	0.77	0.75
	Phil	0.77	1.00	0.74
	Iowa	0.75	0.74	1.00
NoteF4	CAMP	1.00	0.84	0.80
	Phil	0.84	1.00	0.90
	Iowa	0.80	0.90	1.00
NoteG4	CAMP	1.00	0.90	0.92
	Phil	0.90	1.00	0.88
	Iowa	0.92	0.88	1.00
NoteC5	CAMP	1.00	0.86	0.90
	Phil	0.86	1.00	0.85
	Iowa	0.90	0.85	1.00

Figure 3.24 Comparing the correlation between the three different sample sources CAMP, Philharmonia (Phil), and the University of Iowa Electronic Music Studios. The correlogram is scaled from 0 to 1, 1 representing how alike each of the notes are on a particular instrument between the sample sources. **(A)**Flute conducted on HiRes and **(B)**Flute conducted on Optima.

Woodwinds and Brass overall had very high correlation, as depicted in the Flute for example. However, this was not necessarily the case particularly for string instruments. I suspect this has to do with the articulation affecting the decay of the note:



(A) Trumpet Samples from CAMP, Philharmonia, Iowa Wav files HiRes 80IDR

		CAMP	Phil	Iowa
NoteA4	CAMP	1.00	0.51	0.70
	Phil	0.51	1.00	0.79
	Iowa	0.70	0.79	1.00
NoteC4	CAMP	1.00	0.64	0.83
	Phil	0.64	1.00	0.82
	Iowa	0.83	0.82	1.00
NoteF4	CAMP	1.00	0.44	0.72
	Phil	0.44	1.00	0.89
	Iowa	0.72	0.89	1.00
NoteG4	CAMP	1.00	0.73	0.80
	Phil	0.73	1.00	0.87
	Iowa	0.80	0.87	1.00
NoteC5	CAMP	1.00	0.72	0.73
	Phil	0.72	1.00	0.93
	Iowa	0.73	0.93	1.00

(B) Trumpet Samples from CAMP, Philharmonia, Iowa Wav files Optima 80IDR

		CAMP	Phil	Iowa
NoteA4	CAMP	1.00	0.73	0.86
	Phil	0.73	1.00	0.85
	Iowa	0.86	0.85	1.00
NoteC4	CAMP	1.00	0.77	0.85
	Phil	0.77	1.00	0.83
	Iowa	0.85	0.83	1.00
NoteF4	CAMP	1.00	0.63	0.79
	Phil	0.63	1.00	0.88
	Iowa	0.79	0.88	1.00
NoteG4	CAMP	1.00	0.81	0.88
	Phil	0.81	1.00	0.85
	Iowa	0.88	0.85	1.00
NoteC5	CAMP	1.00	0.86	0.87
	Phil	0.86	1.00	0.93
	Iowa	0.87	0.93	1.00

Figure 3.25 **(A)**Trumpet conducted on HiRes and **(B)**Trumpet conducted on Optima.

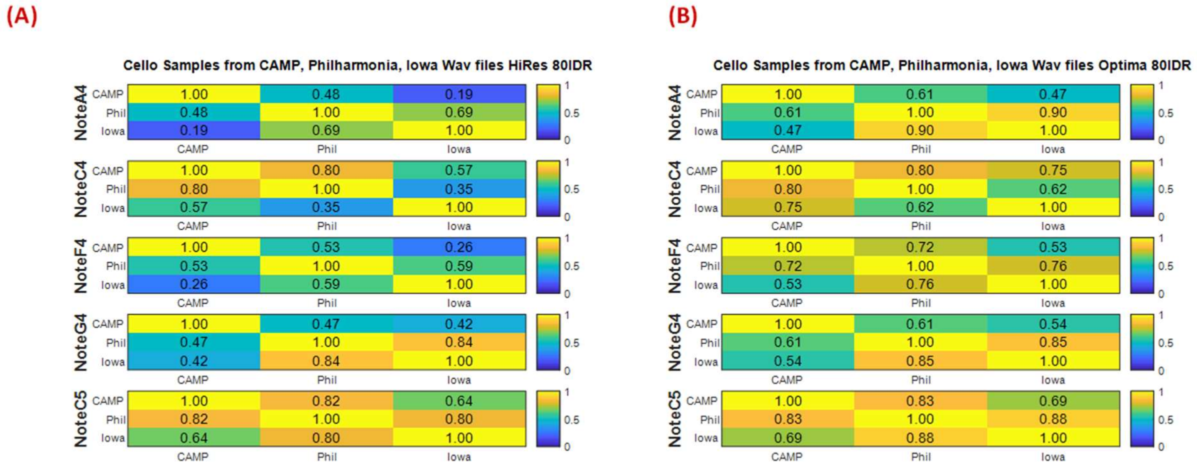


Figure 3.26 **(A)**Cello conducted on HiRes and **(B)**Cello conducted on Optima.

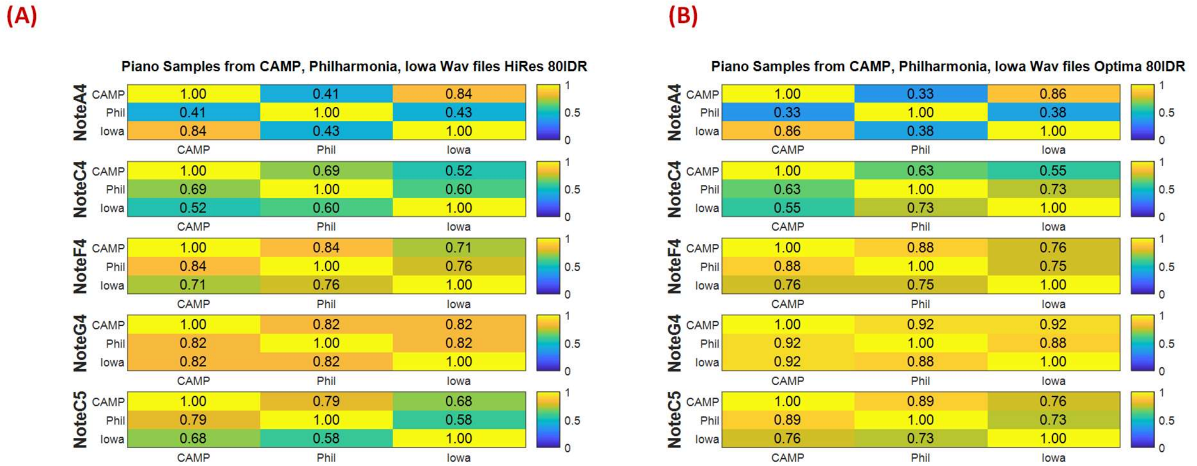


Figure 3.27 **(A)**Piano conducted on HiRes and **(B)**Piano conducted on Optima.

4 Chapter 4: **Discussion**

Through electrodogram analysis and comparisons of correlation between musical samples from the CAMP study, we sought to create a methodology to estimate the distinguishability of instruments and notes for cochlear implants (CIs) using different signal processing strategies. Our results are a very promising start to begin answering the questions around improving the perception of music for CIs. We began by considering how temporal data may affect our results, particularly the binning or averaging of data over time, within each of the CI channels. In Figure 3.5, we showed that both including the 6ms time bins and averaging across time in each channel resulted in what appears to be a normal distribution. For Optima, the standard deviation did not vary depending on the inclusion of temporal information, suggesting that the additional temporal information did not make a difference for Optima as a signal processing strategy. However, there was a significant gap between the average and the temporal data for HiRes, that may suggest temporal information impacts signal processing strategies differently. Another important treatment of the wav files to consider that impacts temporal data is the sampling form each of the sound files. A 200ms window was used to extract each individual wav file, but more of the wave form could be included, for example 300ms or even 700ms. This would include more of the attack and decay of the sound file, which could impact the findings, as well as vary based on the signal processing strategy. It is important to note that participants in the CAMP study had access to all temporal information of the instruments played for them. To summarize, the rest of the analysis was conducted including temporal information within 6ms time bins considering that the standard deviation of the correlations was much smaller compared to averaging the current in each channel.

After determining how to represent the data, we were particularly interested in the relationship between all the combinations of the CAMP wav files and how they would compare. Figure 3.7 through Figure 3.12 show the difference in correlations for different sounds. For instance, 3.7 shows a high correlation between Guitar and Trumpet on A4. Looking at the electrodogram (EL), we can see similar spread of channels being stimulated such as channels 6,8, and 10 for both instruments. Looking at the spectrogram, we can see that the formants are clustered in similar locations around the 0-3000Hz for both instruments. Figure 3.9 shows the opposite relationship, where the spread of channels does not look similar for the Cello and the Saxophone. Looking at these characteristics also apply to comparing the EL and spectrogram between notes in Figure 3.10-3.12. Correlation provides a method for comparing these differences that can be visualized in these figures.

CAMP study results demonstrated specific findings for instruments such as the Flute and Guitar and relationships between the spacing between notes by semitones[21]. We sought to find similar relationship by applying our method of correlations and displayed these relationships through the correlogram in Figure 3.6. Grouping the 8 instruments by their particular note showed a clear relation between notes, appearing as 8x8 grinds within the plot. The relationship between notes and particular instruments also changed based on the signal processing strategy. More of the 8x8 blocks had higher correlations when switching for HiRes to Optima, suggested by the appearance of more blue colored blocks than bright yellow or green blocks. One note that was particularly interesting to look at was the note A, represented by the first 8x8 block on the correlogram. It appeared when comparing all the instruments on the note A4, the correlation is very high as shown through the bright yellow square at that position in Figure 3.6. Interesting enough, the note A4 is typically used in an orchestra to tune all of the instruments. Typically, a woodwind such as the oboe or clarinet will hold the note A while the rest of the orchestra tunes to it. The similarity of the note A between the example instruments in the CAMP study may suggest something particular about the spectral content from the note A4.

To improve the resolution of these analyses, we zoom in further with our correlogram analysis by looking at the correlation between the notes on each instrument. By averaging the correlogram and subtracting on the diagonal, we are able to derive an overall correlation for each of the instruments. Conducting this analysis on both Optima and HiRes produces Figure 3.11, which shows how correlations compare between the different instruments. Based on our methodology, the clarinet would have the best distinguishability out of all the instruments for the CAMP wav files. It had the lowest correlation, which suggests that it would be more successfully identified for the timbre test. The trumpet on the other hand would give CI patients the most difficulty, having the highest correlation value between the instruments. Revisiting the results of the CAMP study in 2008, some of these results are expected. For instance, identifying the flute would also be relatively difficult considering it is the instrument with the second highest correlation. This is similar to the CAMP study finding that the flute had one of the worst identification scores for CI patients. In the CAMP study, the string instruments had relatively higher identification percentages compared to the instruments as shown in Figure 3.1. Our methodology showed a similar relationship with the strings having lower correlations compared with other instruments families. It was interesting to find that the trumpet had the highest correlation for our methodology, as it was found in the middle for the CAMP study. To follow up with these findings, conducting the CAMP study with CI patient of the sampled wav files would serve as a basis of accurate our predictions were for instrument identification.

In addition to analyzing the instruments, the same analysis was conducted for each of the 5 notes for the study. The results, as shown in Figure 3.15, were expected considering the frequency range of each of the note. The note C4, the lowest note within the CAMP audio files, had the lowest correlation while the note C5, the highest note, had the highest correlation. This relationship is present for both HiRes and Optima. Many studies have shown that CI users are able to identify low frequencies better than high frequencies due to the limited frequency range of the CI[27]. This relationship is apparent from the ascending order of the frequency of notes that is consistent for both signal processing strategies. A relationship between the notes is also visible when revisiting Figure 3.6. The notes that are in closer proximity to each have a higher correlation than the notes further spaced apart. For example, notes such as F4 and G4 which are only a whole step apart are highly correlated, compared to the relationship between A4 and C5 or F4 and A4. It is also interesting to note that relationship such as A4 and C5 or F4 and A4 are described as a 3rd apart interval wise (in other words 4 semitones apart). The CAMP studies from both 2008 and 2015 also showed a relationship between increasing intervals between the notes and the ability to better distinguish the difference between pitch. Nimmons et al. demonstrated a decreasing range of pitch discrimination on specific formants as the pitch increased [21]. W. R. Drennan et al. had comparable averages of around 3 semitones or higher for pitch discrimination [6]. Increasing the interval for this study however does not necessarily show the same relationship, for example a 5th interval between C4 and G5 is more highly correlated than the 3rd interval between F4 and A4. These findings may suggest a greater influence of the instrumental group on the notes, as well as loss of spectral information as the notes ascend higher in pitch. An indicator of this is looking at the highest C, C5, which is the least correlated between all of the notes. As it is the highest pitched note, it is more likely to be missing more formants that are a characteristic to the instruments and the notes harmonics. Thus, this loss of information could be weighed more compared to the lower frequency notes.

It is also important to consider multiple samples of the same note on an instrument to verify what these correlations mean. Acquiring multiple sources, such as the Philharmonia and Iowa samples, allows us to feel more confident about what the correlations are saying. If we compare the correlation of the audio files from CAMP, Philharmonia, and Iowa on the same note on an instrument, we can have a better idea of how well that particular note on the instrument is represented. Figure 3.16 through Figure 3.19 illustrate this point and give an example of different audio file relationships for each musical instrument family. From Figure 3.16 and Figure 3.17, the correlations between the three wav files sources are relatively high and close to 1. However, Figure 3.18A has low correlations between CAMP and Iowa on note A4 or CAMP and Philharmonia on note G4. Figure 3.18B also shows high correlations between CAMP and Iowa on note G4 and CAMP and Philharmonia on note C4. These variations depict the unique nature of music in real life. When choosing notes and instruments from multiple sources, there is a random effect to how the musical signal presents itself. The location the instrument was recorded in, the brand or age of the instrument was used, ad the musician playing are all factors that can impact the tone and therefore the spectral information of a single note. Normalizing the data will not change the malleability that even a single note carries. To mitigate this affect, multiple samples need to be acquired from multiple places to better replicate coming in contact with different sonic sources in the real world. This study attempted that by acquiring the three samples from CAMP, Philharmonia, and Iowa. However, it would be ideal to obtain over 20 samples of the same note on an instrument and see what the correlation converges towards.

Having multiple samples of the same note on an instrument did enable the analysis of comparing the two signal processing strategies in the paper: HiRes and Optima. By combining all the notes (n=15) and the instruments (n=24) from the 3 samples, we were able to compare the significance in the difference of correlation between HiRes and Optima. The difference of correlations between instruments comparing HiRes and Optima were significant with a p-value of 0.0190. Optima had lower correlations than HiRes as shown by Figure 3.18, meaning it would be easier to distinguish between instruments using an Optima strategy. The difference of correlations between notes comparing HiRes and Optima were also statistically significant, with a p-value of 0.0445. HiRes had lower correlations than Optima as shown in Figure 3.19, meaning it would be easier to distinguish between notes on HiRes.

Through these analyses, we were able to show the effectiveness of using electrodograms (ELs) and correlation coefficients as a way to compare cochlear implant processing of different musical signals. ELs are spectrally and temporally able to represent musical notes and instruments and are somewhat comparable to spectrograms. Through examples of multiple Els from different instruments and notes, we are able to see distinct similarities and differences in the range of channel stimulation and total current to a particular channel. We took this one step further using correlograms that provided a tool to quantify and compare EL data associate these differences statistically. Instruments that had a low correlation like the Clarinet had more spectral and temporal differences, which would indicate an instrument that is more distinguishable from others. On the other hand, notes like C5 that had a high correlation had similar characteristics to other signals that make it more difficult to discern from other notes. We were also able to show that Optima had a better association of instrument distinguishability, while HiRes had a better association of note distinguishability.

The purpose of this thesis is to provide a foundation to analyzing musical signals for cochlear implants. The samples used in this thesis were representative of common instrumental groups, but much more can be done to study the relationship between more notes. In particular, having more examples than CAMP, Philharmonia, and Iowa of the same instrument on a particular note would provide more confidence of our estimates of distinguishability. Additionally, using correlation coefficients would also encourage encoding and engineering musical data to optimize the spectral and temporal differences of inputs. Extracting the note and instrumental composition of a piece and running a correlation is one application of this methodology. For example, studying how distinguishable the instrumentation of one of the cochlear implant compositions by Natasha Anderson or Ben Harper can set up experiments for what sonic elements make a difference for CI user's perception. We could also change parameters such as signal processing strategy, pulse rate, and thresholds to see which settings lower the correlation. Electrodogram and correlation analysis are a concrete way towards fine-tuning the listening experience for CI users and indicates what changes to musical signals could have the greatest impact on improving distinguishability of notes and instruments.

More importantly, we are working towards tailoring a better listening experience for CI users. Technology will continue to advance, and maybe we will achieve a CI that is comparable to hearing acoustically in all environments. But there is an undeniable impetus to enjoy music, contrary to frustrations from the limitations of the device and the difficulty of processing musical signals. Despite this, people are still receiving implantations knowing that the outcome to enjoying music could be worse than when they started. They take this risk in hope that they can finally or once again experience music the way they want to. We can begin working on a solution that explores an integral component to hearing music, and that is the sound itself.

Creating comparable ways such as correlation comparisons and electrodogram visualizations give us quantitative ways to improve the listening experience for CIs. On the other hand, understanding the stories of CI users, what communities they identify with, and what kind of music they appreciate is even more informative. It teaches us to consider the unique experience of hearing that each of us possess and how science can work towards including the stories of the individuals that it impacts.

5 Appendix

5.1 Electrodograms of All CAMP Instruments on HiRes and Optima

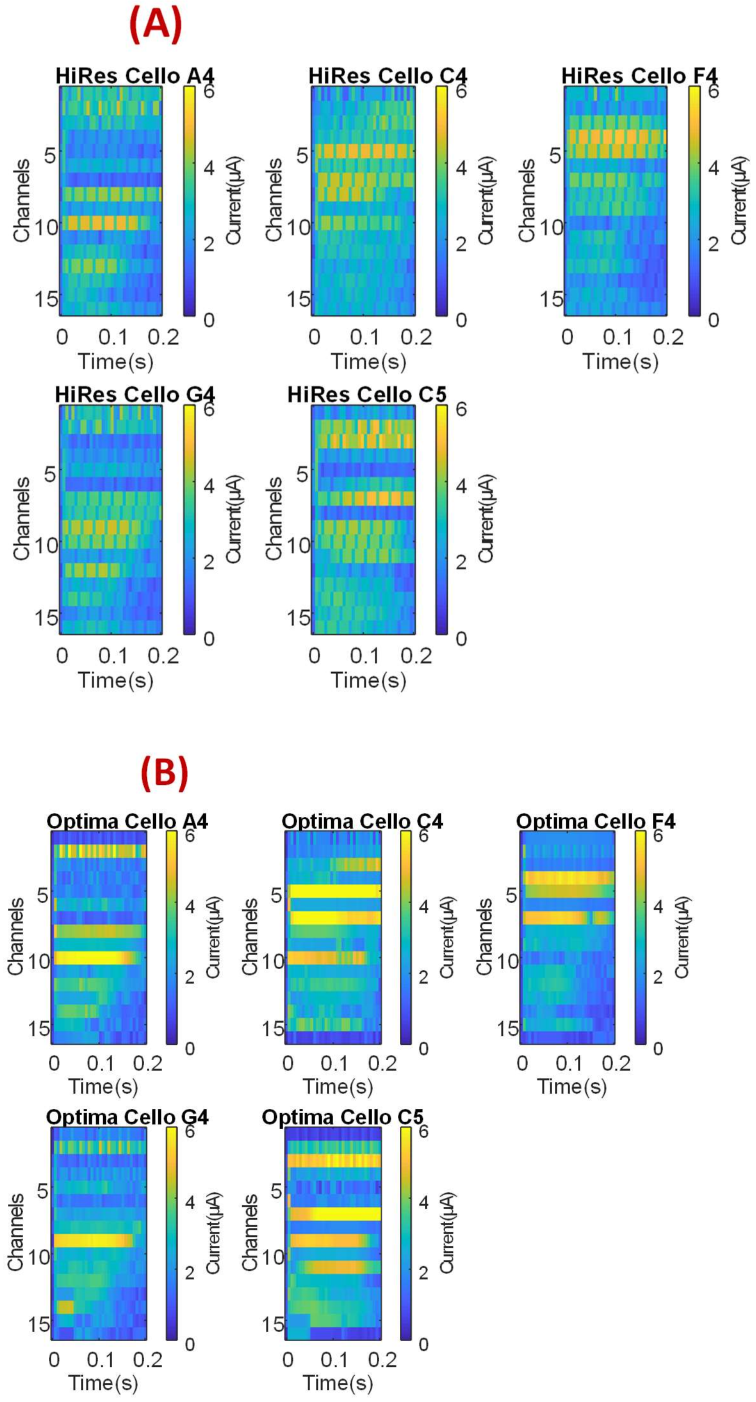


*Figure 5.1 ELs for **(A)**HiRes and **(B)**Optima for Cello*

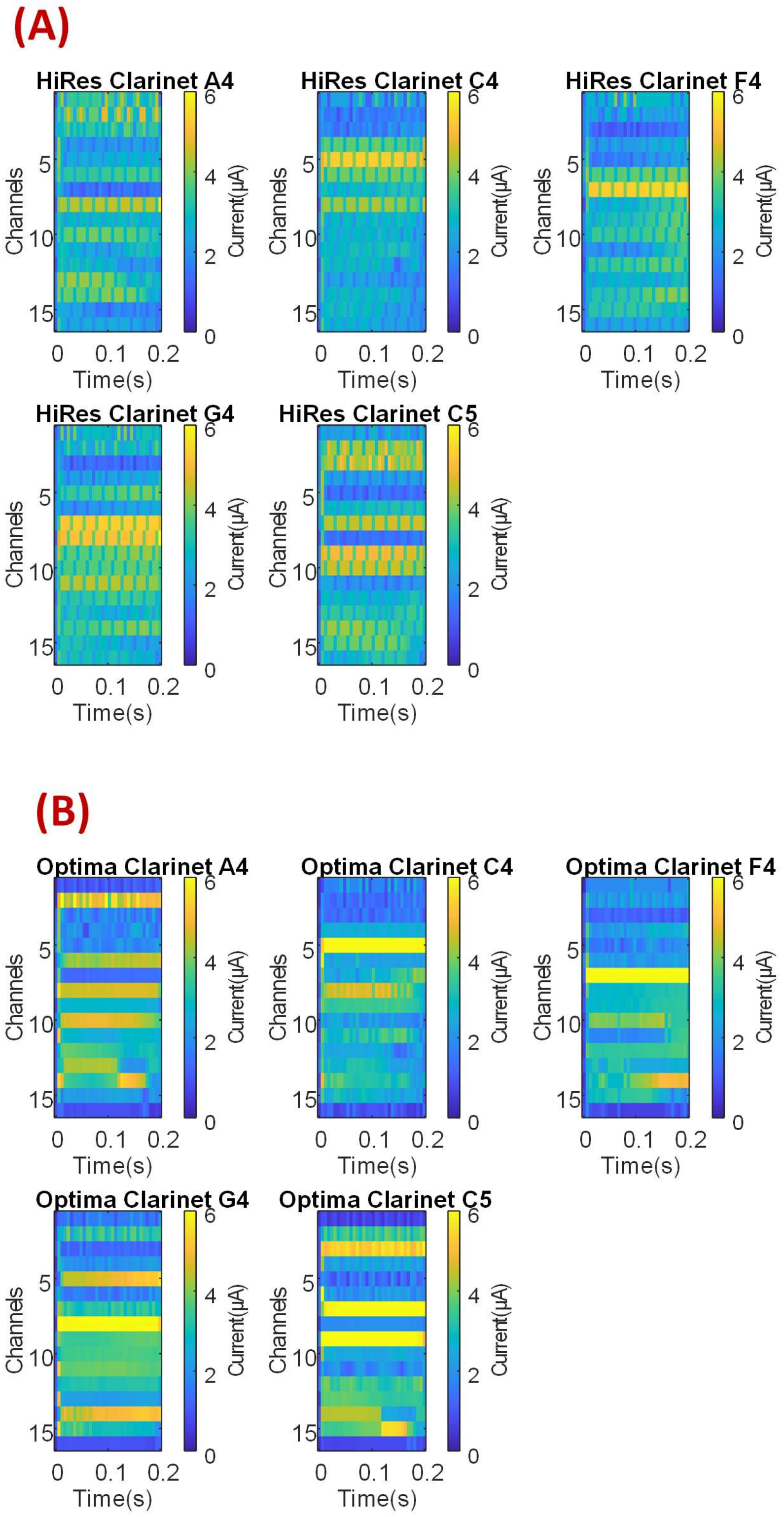
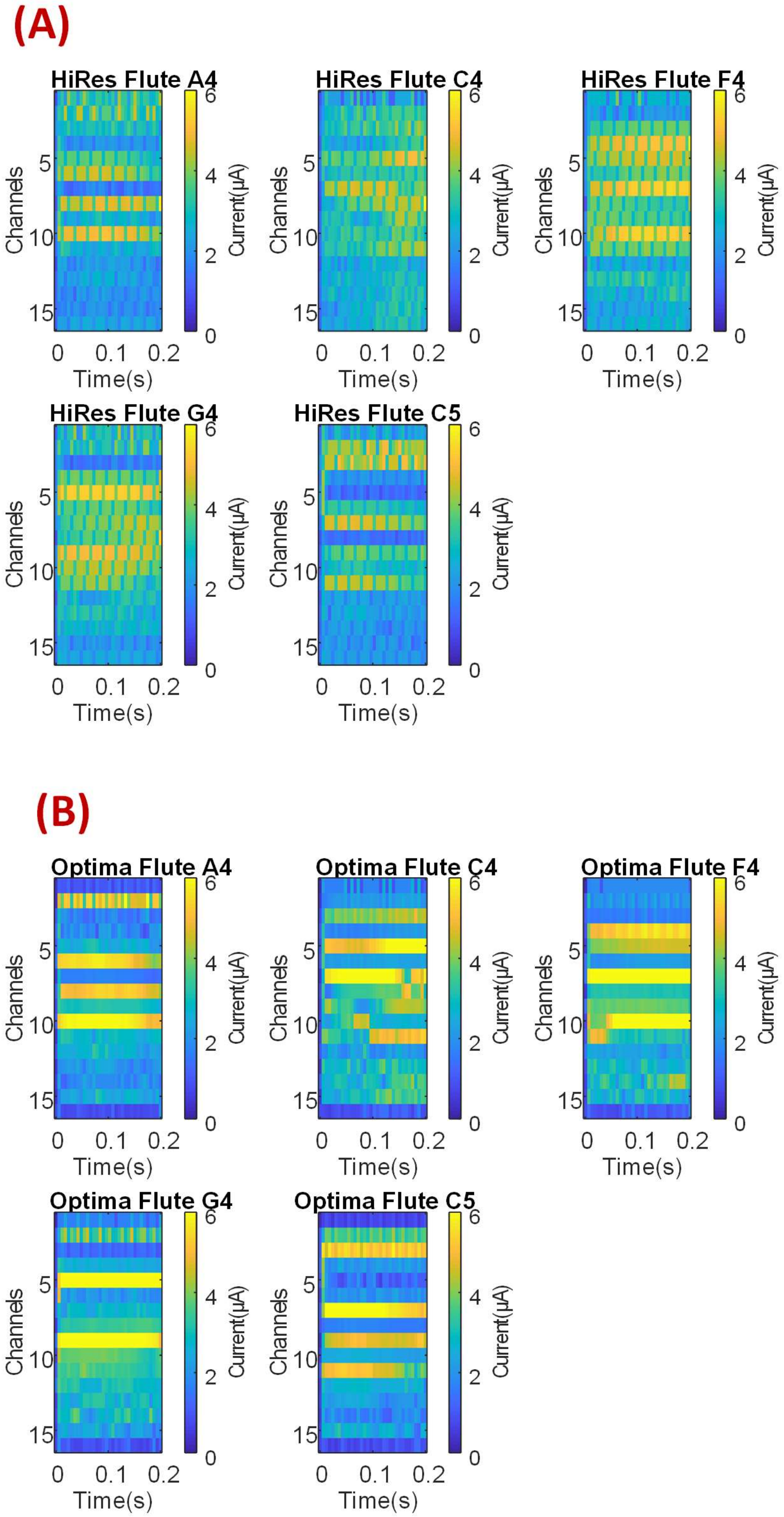


Figure 5.2 ELs for ***(A)****HiRes and* ***(B)****Optima for Clarinet*



HiRes Flute A4

HiRes Flute C4

HiRes Flute F4

HiRes Flute G4

HiRes Flute C5

Optima Flute A4

Optima Flute C4

Optima Flute F4

Optima Flute G4

Optima Flute C5

*Figure 5.3 ELs for **(A)**HiRes and **(B)**Optima for Flute*

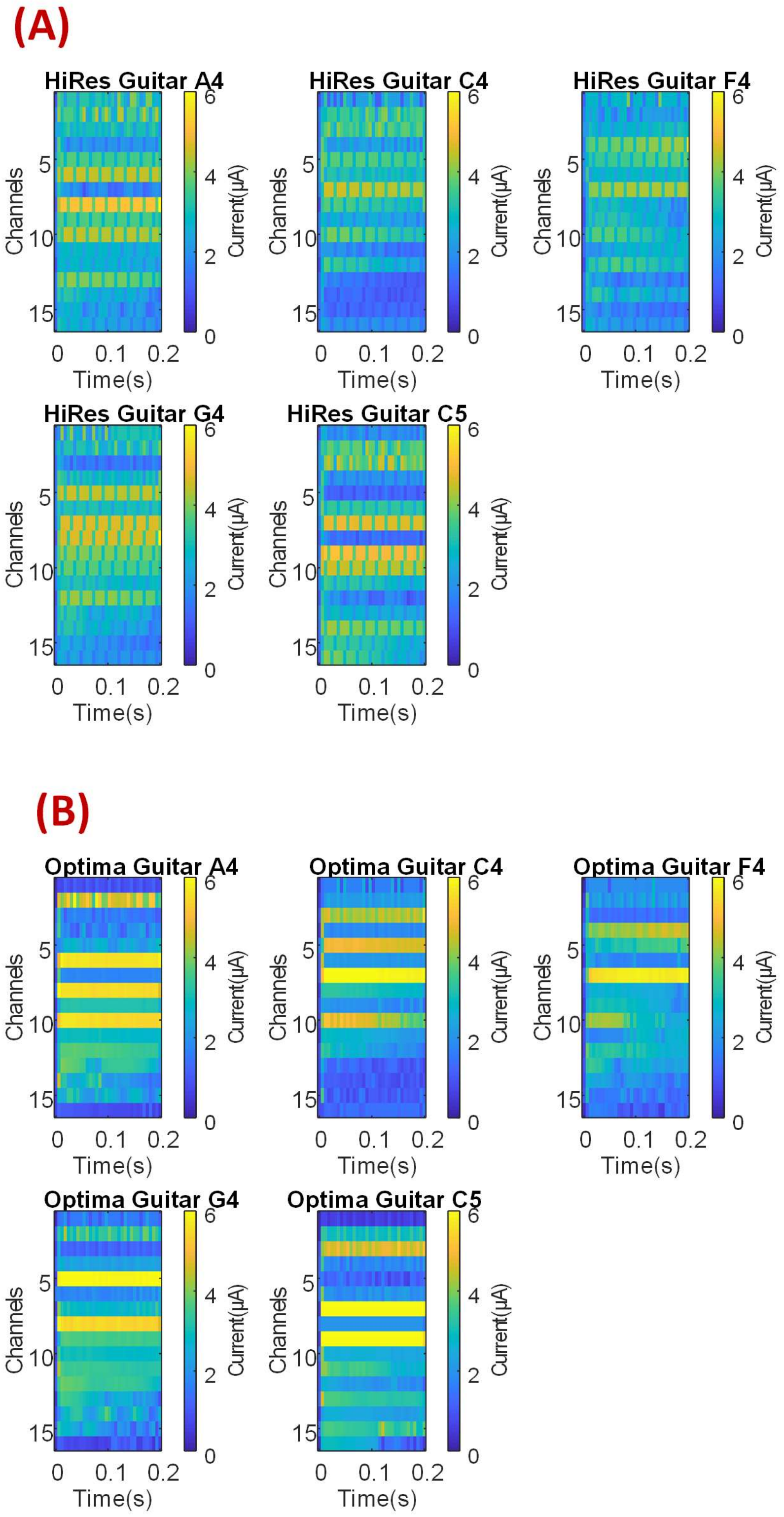


*Figure 5.4 ELs for **(A)**HiRes and **(B)**Optima for Guitar*

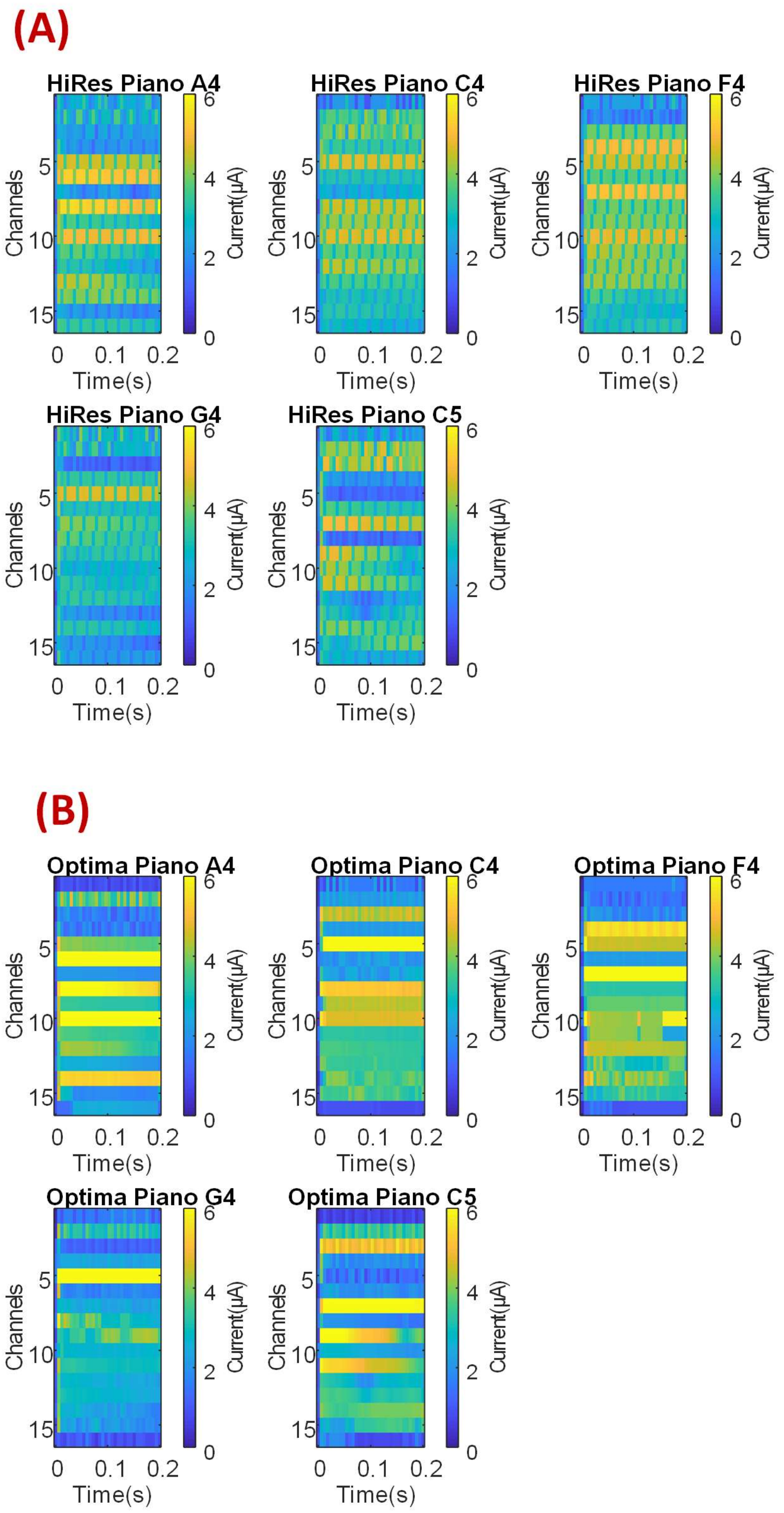


*Figure 5.5 ELs for **(A)**HiRes and **(B)**Optima for Piano*

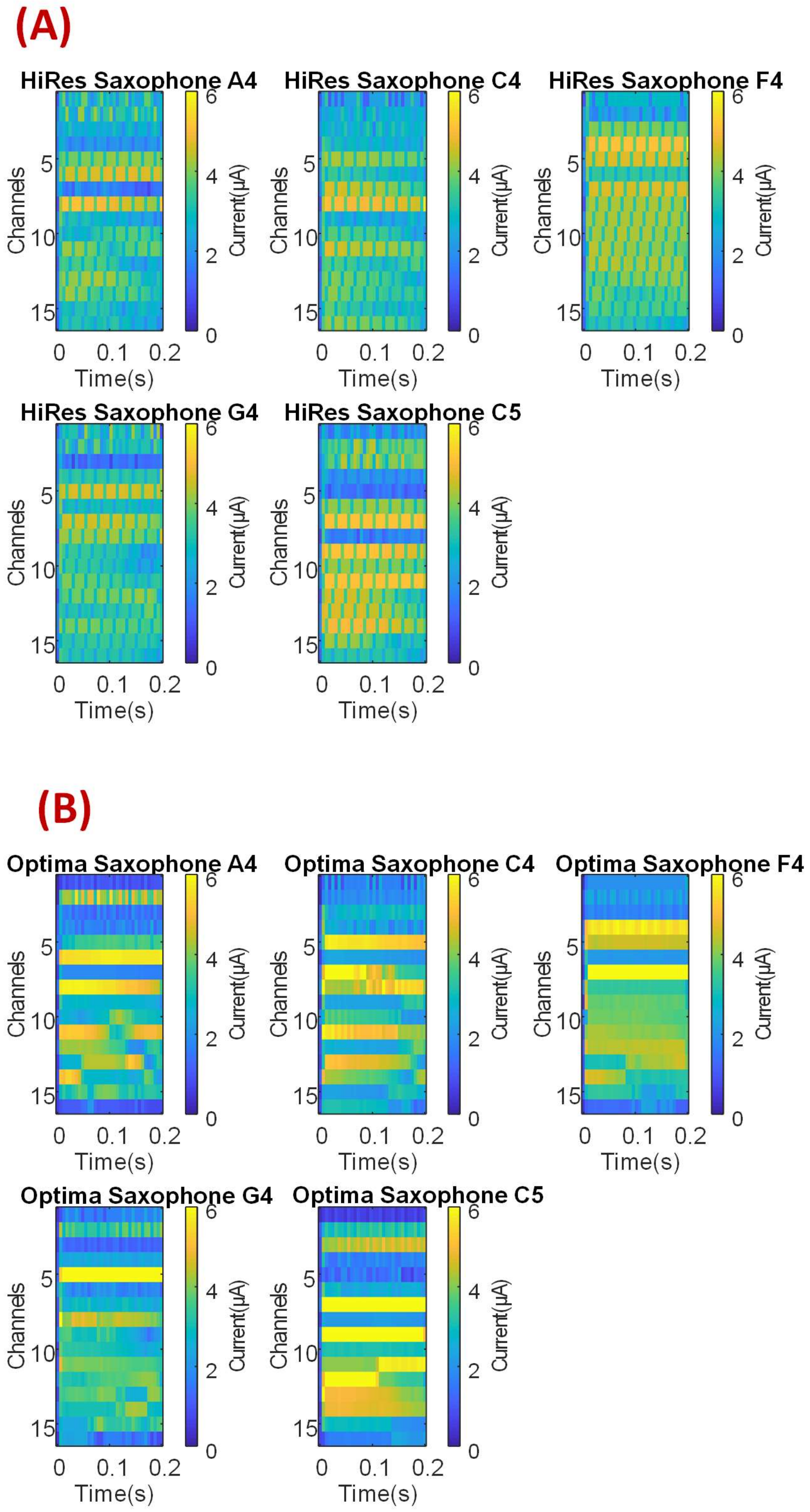


*Figure 5.6 ELs for **(A)**HiRes and **(B)**Optima for Saxophone*

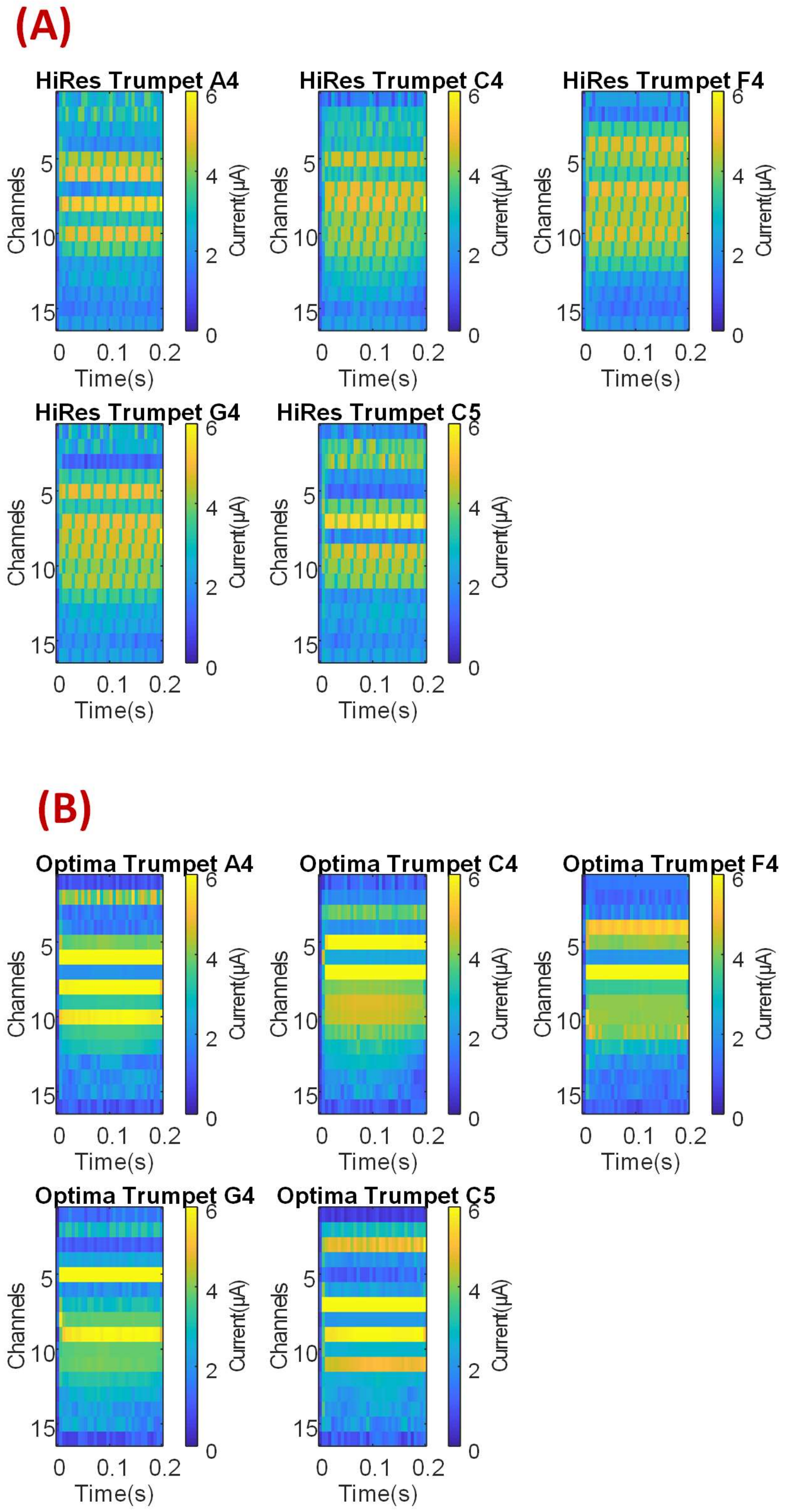


Figure 5.7 ELs for ***(A)****HiRes and* ***(B)****Optima for Trumpet*

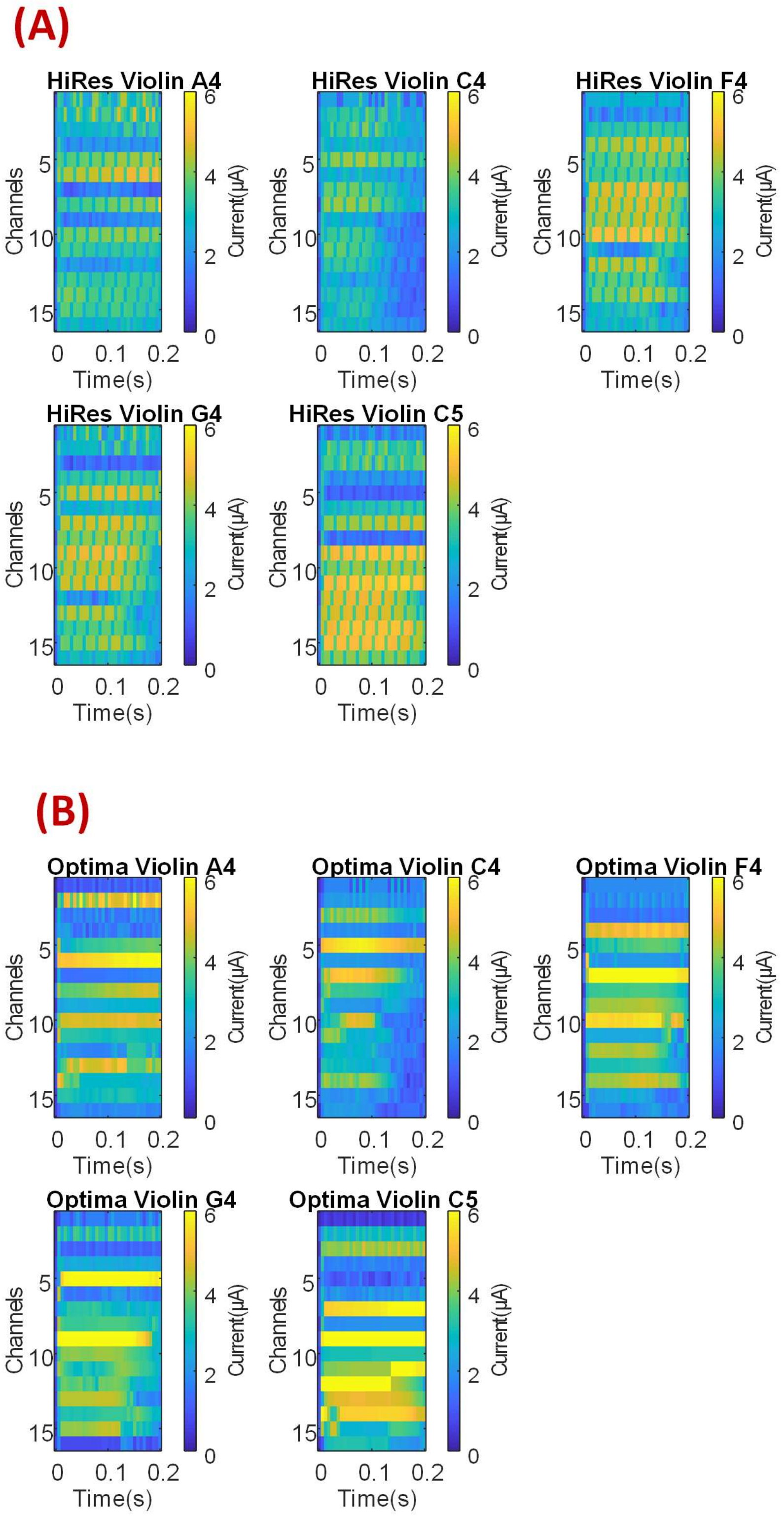


*Figure 5.8 ELs for **(A)**HiRes and **(B)**Optima for Violin*

5.2 Additional Correlation Coefficients Comparing CAMP, Philharmonia, and Iowa Instrument Samples

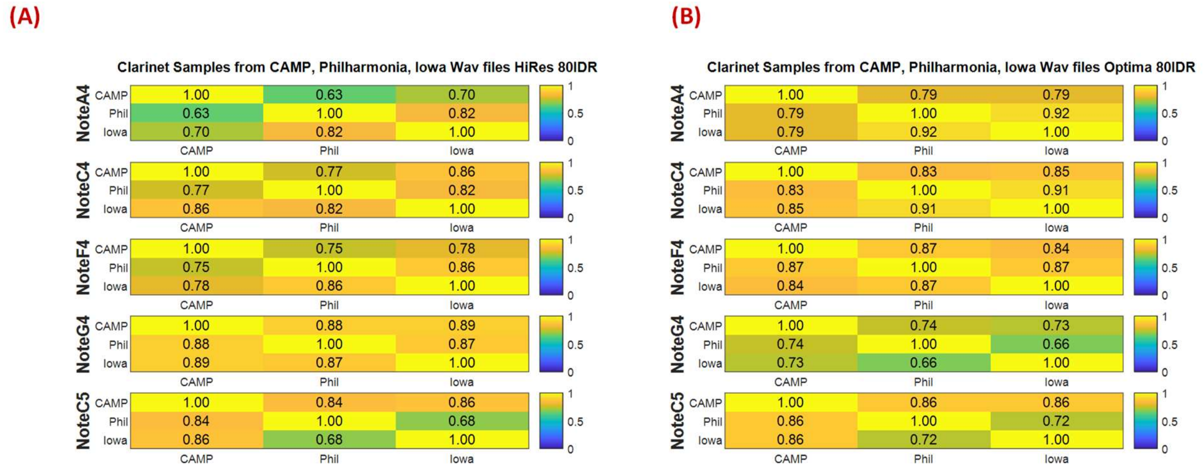


*Figure 5.9 Correlation coefficients comparing CAMP, Phil, and Iowa samples for **(A)** HiRes and **(B)** Optima on Clarinet*

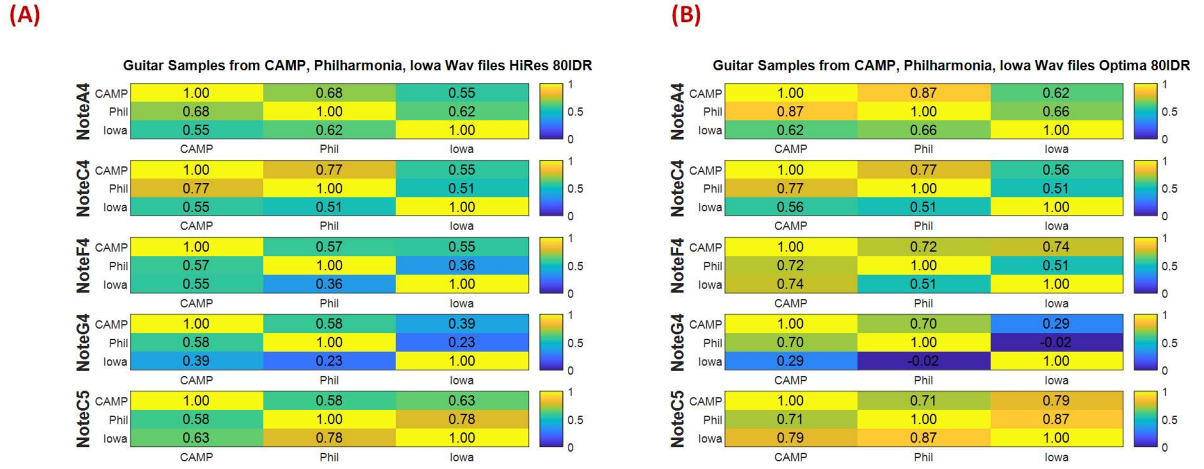
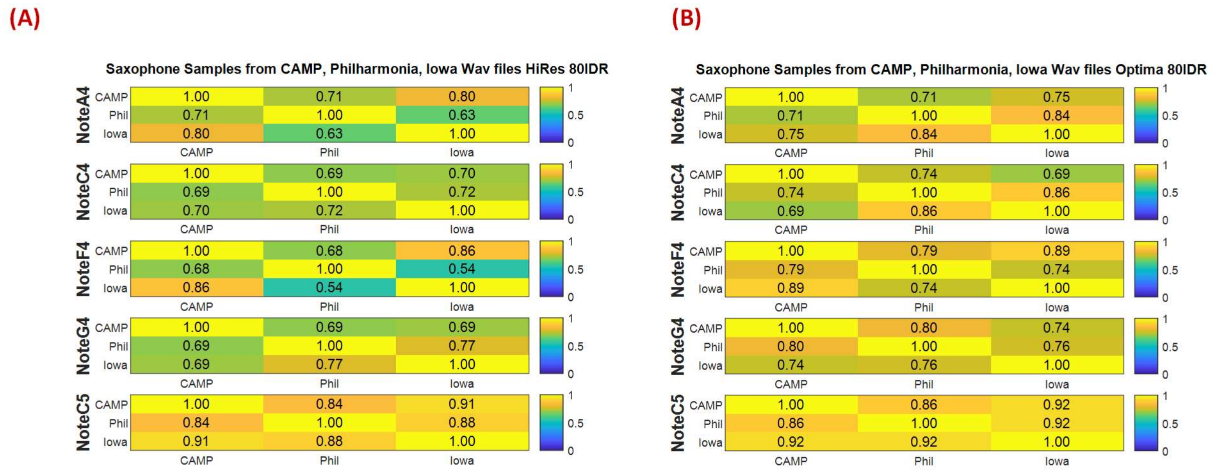


*Figure 5.10 Correlation coefficients comparing CAMP, Phil, and Iowa samples for **(A)** HiRes and **(B)** Optima on Guitar*



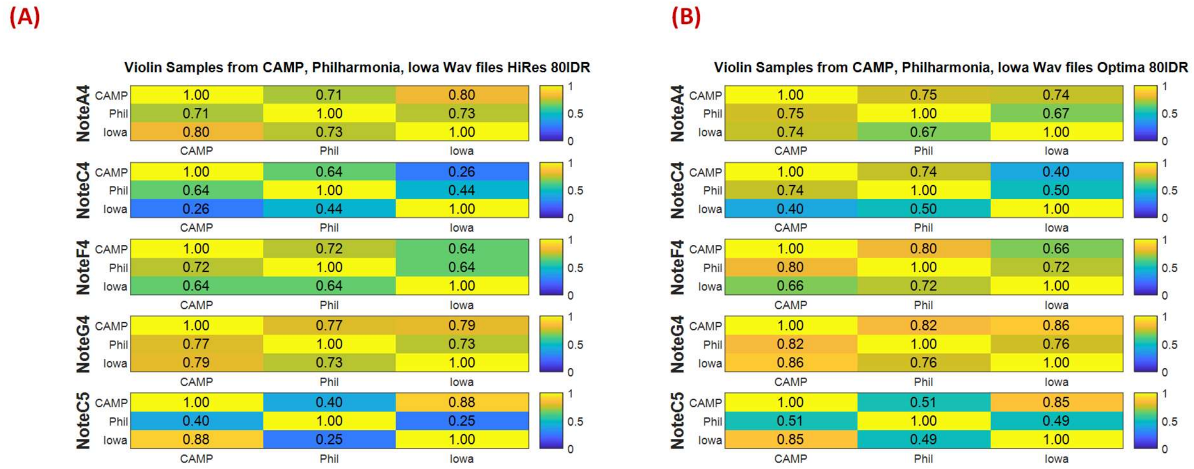
(A) Saxophone Samples from CAMP, Philharmonia, Iowa Wav files HiRes 80IDR

		CAMP	Phil	Iowa
NoteA4	CAMP	1.00	0.71	0.80
	Phil	0.71	1.00	0.63
	Iowa	0.80	0.63	1.00
NoteC4	CAMP	1.00	0.69	0.70
	Phil	0.69	1.00	0.72
	Iowa	0.70	0.72	1.00
NoteF4	CAMP	1.00	0.68	0.86
	Phil	0.68	1.00	0.54
	Iowa	0.86	0.54	1.00
NoteG4	CAMP	1.00	0.69	0.69
	Phil	0.69	1.00	0.77
	Iowa	0.69	0.77	1.00
NoteC5	CAMP	1.00	0.84	0.91
	Phil	0.84	1.00	0.88
	Iowa	0.91	0.88	1.00

(B) Saxophone Samples from CAMP, Philharmonia, Iowa Wav files Optima 80IDR

		CAMP	Phil	Iowa
NoteA4	CAMP	1.00	0.71	0.75
	Phil	0.71	1.00	0.84
	Iowa	0.75	0.84	1.00
NoteC4	CAMP	1.00	0.74	0.69
	Phil	0.74	1.00	0.86
	Iowa	0.69	0.86	1.00
NoteF4	CAMP	1.00	0.79	0.89
	Phil	0.79	1.00	0.74
	Iowa	0.89	0.74	1.00
NoteG4	CAMP	1.00	0.80	0.74
	Phil	0.80	1.00	0.76
	Iowa	0.74	0.76	1.00
NoteC5	CAMP	1.00	0.86	0.92
	Phil	0.86	1.00	0.92
	Iowa	0.92	0.92	1.00

*Figure 5.11 Correlation coefficients comparing CAMP, Phil, and Iowa samples for **(A)** HiRes and **(B)** Optima on Saxophone*



(A) Violin Samples from CAMP, Philharmonia, Iowa Wav files HiRes 80IDR

		CAMP	Phil	Iowa
NoteA4	CAMP	1.00	0.71	0.80
	Phil	0.71	1.00	0.73
	Iowa	0.80	0.73	1.00
NoteC4	CAMP	1.00	0.64	0.26
	Phil	0.64	1.00	0.44
	Iowa	0.26	0.44	1.00
NoteF4	CAMP	1.00	0.72	0.64
	Phil	0.72	1.00	0.64
	Iowa	0.64	0.64	1.00
NoteG4	CAMP	1.00	0.77	0.79
	Phil	0.77	1.00	0.73
	Iowa	0.79	0.73	1.00
NoteC5	CAMP	1.00	0.40	0.88
	Phil	0.40	1.00	0.25
	Iowa	0.88	0.25	1.00

(B) Violin Samples from CAMP, Philharmonia, Iowa Wav files Optima 80IDR

		CAMP	Phil	Iowa
NoteA4	CAMP	1.00	0.75	0.74
	Phil	0.75	1.00	0.67
	Iowa	0.74	0.67	1.00
NoteC4	CAMP	1.00	0.74	0.40
	Phil	0.74	1.00	0.50
	Iowa	0.40	0.50	1.00
NoteF4	CAMP	1.00	0.80	0.66
	Phil	0.80	1.00	0.72
	Iowa	0.66	0.72	1.00
NoteG4	CAMP	1.00	0.82	0.86
	Phil	0.82	1.00	0.76
	Iowa	0.86	0.76	1.00
NoteC5	CAMP	1.00	0.51	0.85
	Phil	0.51	1.00	0.49
	Iowa	0.85	0.49	1.00

*Figure 5.12 Correlation coefficients comparing CAMP, Phil, and Iowa samples for **(A)** HiRes and **(B)** Optima on Violin*

5.3 Questions for Cochlear Implant Interviewee:

How long ago did you receive a cochlear implant and what motivated you?

How do you perceive your own hearing abilities? Are there any communities that you identify with whether the deaf community, a CI community, or others?

Do you believe there is an established community or culture for CI users? Is CI users the right term to identify the community?

Ideally, how would a cochlear implant function for you?

Many scientific studies make a delineation between “normal hearers” and “CI users” in their papers. In what ways have you grappled with normalcy?

How would you describe your musical background? For instance, do you perform, understand theory or are a part of particular musical culture, or simply listen to music frequently?

Have you done any musical training with your cochlear implant?

In what ways have you had to adapt to listening to music and in what instances does it become too much to listen to a piece?

How often do you listen to music now that you have the Cochlear Implant? Has this changed from before you had the implant?

Are there particular sounds that you enjoy listening to more than others? Were any of these sounds surprising to you?

What sounds are you able to make out more than others? Are there any that really annoy you?

Are you able to identify different instruments? Can you think of any that you are able to identify more easily than others?

How long do you think it took for you to start comprehending a sound as music through your implant? Can you describe how you knew?

Is there a particular style or genre of music you enjoy listening too? Has this changed since the time you received you implant?

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