A Case Study of an Advanced Violinist with a Cochlear Implant

Assessing high-level pitch, timbre, and melodic perception in a university student with a cochlear implant

Master's Thesis Paper

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Abstract

Background: A review of literature shows that cochlear implant (CI) users face difficulties in terms of music interpretation when compared to regular hearing (RH) counterparts. The electrically pulsing nature of the CI acts differently than sound waves in a normally functioning ear, leading to different interpretations of musical concepts such as pitch or timbre. An exceptional case however has been observed in a university-level violinist with bimodal hearing (congenitally deaf in the right ear, and with very minimal residual hearing in the left; they use one CI and one hearing aid) at the University of Ottawa.

Objective: This study will compare the pitch recognition, timbre preference and audiation (linked to pitch and rhythmic perception) abilities between an exceptional CI user and case-control RH violinists. Data has previously been collected on CI users not playing the violin due to CI technology's limitations in pitch processing. Since the violin is considered a pitch-heavy instrument to play, it is expected that the study participant has exceptional pitch recognition skills when compared to other CI users (and perhaps RH peers), while still demonstrating comparable timbre preference and rhythmic audiation abilities to an RH comparison group.

Method: Three tests were administered relating to pitch recognition on a violin-like interface, timbre preference between two heard tones, and an Advanced Measures of Music Audiation (AMMA) test for general musical knowledge in pitch and rhythm-based melodic discrimination. Results were compared between the critical case-study with CIs and RH control participants to quantify a basis in pitch perception, timbre preference and melodic audiation (applied to pitch and rhythm) skills.

Implications: The study participant demonstrated comparable timbre preference and rhythmic discrimination skills to an RH comparison group. The study participant demonstrated pitch perception skills higher than previously tested CI users, despite being lower than the RH comparison group. The CI-using study participant would have developed these higher-than-average pitch perception skills through rigorous early-age training, and passion and persistence of music training on a pitch-heavy instrument despite known recommendations. This sheds light on the CI's technology not necessarily limiting users' choice of instrument due to its pitch processing, despite previous recommendations.

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1. Introduction

The cochlear implant (CI) has been revolutionary in terms of breaking barriers for individuals with profound hearing loss. Since its inception in the 1980s, the technology has not ceased its refining process, allowing a greater spectrum of sound perception to its users. Using a digital signal processor, the implant bypasses the acoustic hearing mechanisms of the ear, and stimulates the auditory nerve directly by electrical signals, providing the brain with the same stimulation as regular (or typical) hearing (RH) would (Clark, 2015). However, studies and usage of this implant quickly revealed that this different kind of sound perception, while reducing primary communication barriers for individuals with hearing loss, created different barriers instead relating to the quality, range and appreciation of the processed sound.

The CI is a surgical prosthesis enabling people with sensory hearing loss to perceive sound through electric stimulation of the auditory nerve, instead of the typical acoustic hearing process. This tool was an important step towards bridging the gap between facilitating hearing, but also communication for deaf or hard-of-hearing people. Gfeller (2007) describes how this led to the significant transition in incorporating deaf and hard-of-hearing students in the mainstream RH classroom in North America. Despite the benefits to hearing and communication, this integration of CIs was not as seamless as was hoped, as it became quite clear that CI users often described the sound quality of music to be unpleasant, and performed with much less accuracy in pitch, melody, and timbre recognition in classroom exercises.

The appreciation of music by CI users has since been a very popular topic for research (Looi & She, 2010; Petersen et al., 2015; Gfeller et al., 2012; Gfeller et al., 2019a). Research is being made in advancing technologies in hopes of developing CIs with advanced bionic technology that might improve the spectral resolution of sound transmitted electrically to the user with higher resolution of sound and faster processing speed of the device (Adams et al., 2014). The intricacy lies specifically in the way that CIs alter pitch and timbre, and how adjusting these factors might give CI users a better appreciation and musical experience overall.

Musicology has a lot to benefit from this new perspective on music listening and appreciation. Holmes (2017) discusses how Dame Evelyn Glennie, a profoundly deaf professional musician and advocate for the Deaf community, works towards broadening the idea of what sound and music can be. Deaf and hard-of-hearing people can perceive and listen to sounds in entirely fulfilling ways, as long as methods are taken to eliminate barriers that they face when compared to RH people. Methods can include some advancements in CI technology, or even redefining the listening environment, and the type of sound or music being heard. It is by redefining the concept of music appreciation that it becomes clear how the deaf community is just as capable of appreciating music to a fulfilling extent. The redefinition of music for the deaf community must be done in parts: redefining the listener, and redefining musicality and musical listening, and redefining musical listening, allowing us to consider which aspects are integral to musical appreciation and performance, and which barriers would need to be adjusted for a musician with CIs to excel musically. Through this investigation, it might also be feasible to shed light on which factors were important to our violinist case-study in terms of interpreting music and achieving a high-level in music understanding and performance, by determining how they perceive music appreciation through a CI.

On average, CI users report a vastly different appreciation of sounds and specifically music when compared either to their previous experience with RH (Gfeller et al., 2012) or even their hypothetical perception of RH appreciation, creating stigma within the deaf community and leading to discouragement in terms of musicianship and adding social barriers to the way music is played and perceived for CI users (Looi & She, 2010). There also exists quantifiable differences in the way a CI interprets musical concepts when compared to RH, giving CI users not only a perceived different listening experience, but a neurological one as well (Petersen et al., 2015). The most widely studied musical difficulty for CI users is pitch perception (Innes-Brown et al., 2013; Stabej et al., 2012; Vongpaisal et al., 2006; Kim et al., 2015), based on how the intricacies of pitch discrimination can get lost in the electrical stimulation of the CI, when compared to normal acoustic hearing. Studies have also shown timbre and instrument choice to be difficult concepts to grasp at times for CI users, but that these can be improved with musical therapy and training (Torppa & Huotilainen, 2019; Baheux, 2019; Chen et al., 2010; Rochette et al., 2014; Yennari, 2010; Gfeller et al., 2019a).

Musical training has been shown to offer many advantages to CI users in terms of speech development (Wang et al., 2011; Baheux, 2019; Rochette et al., 2014), music appreciation in everyday life (Gfeller et al., 2019a) and even emotional response (Yennari, 2010). However, the most fundamental advantage CI users can pull from early musical training is the ability to better understand the musical concepts discussed above (pitch, rhythm, timbre) to a level beyond what is understood by CI users with no musical training (Chen et al., 2010; Rochette et al., 2014; Torppa & Huotilainen, 2019; Baheux, 2019). The same can be said even of familial involvement in music, leading to a higher interest and a more important role music might have in a CI user's life (Gfeller et al., 2012). Finally, exposing deaf individuals to music training and the beneficial effect it has in countering the difficulties of electrically induced hearing permits CI users to take ownership of their music or sound appreciation, and transform it into something unique to them. It is by redefining these conventions of what it means to "hear music", "appreciate music" and even to "be a musician" that CI users can break through social, electro-acoustical and psychological barriers led on by their difference in hearing ability (Holmes, 2017).

The case-study will investigate the extraordinary case of a prelingually deaf violinist who has achieved a remarkable university-level in musicianship. Not only is the level of achievement in music remarkable despite known barriers created using a CI, but the instrument of choice, the violin, is known to be a pitch-sensitive instrument. Since, as seen above, pitch is a musical concept that is more difficult to grasp through CIs, the level of achievement reached by this deaf violinist merits exploration (Torppa & Huotilainen, 2019; Hsiao & Gfeller, 2012).

2. Review of Literature

Research in the field of music education and deafness is often divided in two main populations of CI users - music education for individuals with prelingual deafness, and non-prelingual deafness. The ability an individual might have in terms of previous experience with regular hearing, music listening or playing is an entirely different barrier than an individual born with profound deafness, or who might never have experienced regular hearing. A lot of research in deafness and music education is catered toward prelingually deaf children in early development stages, as their sensory experience has the most to benefit from music education for their sound perception, and even non-musical development (Trehub et al. 2009; Rochette et al., 2014; Baheux, 2019). This case study will focus on an individual who went through similar music classes as a prelingually deaf child with CIs, and the accommodations that they learnt along the way to enlighten their musical development in young adulthood. The following literature review shall therefore be split into two parts: summarizing literature around music education in prelingually deaf children, and literature about continuous education for prelingually deaf young adults and adolescents with CIs.

2.1 Musical Education in Prelingually Deaf Children

Children can get CIs beginning at 10-12 months of age, with only a slight risk of minor complications, and studies have tried to focus on which aspects of a child's auditory learning might be different because of this device (Rochette et al., 2014). Music educators have a slight advantage in this field of research, as music education goes hand-in-hand with auditory development, either through listening, playing, or movement, making music education for deaf children crucial for auditory learning. Music education helps towards learning musical perception and appreciation, and that it can even aid with non-musical development within a deaf child (Trehub et al. 2009; Rochette et al., 2014; Baheux, 2019). In addition, in combination with other factors, it is possible to build best practices and methods tailored around musical education to maximize the efficiency of a child's auditory learning. The following sections will explore this intersection between early-age music education and the reasons why and how it might enhance a prelingually deaf child's auditory perception post-implantation.

2.1.1 Musical perception in prelingually deaf children

Musical and auditory perception is a large field, pertaining in this case to any quantifiable element of music to be heard, either by RH or CI. Most researched elements of music listening often include pitch, rhythm, or timbre. The usage of a CI greatly affects the way a child listener perceives some of these aspects, simply by the nature of electrical stimulation instead of the perception of physical sound waves. Innes-Brown and colleagues (2013) study 11 children with CIs, and 9 children with RH, and worked on their rhythm, pitch, and instrument recognition skills in the context of regular musical activity sessions. Notably, there was little to no difference in rhythmic perception between groups, however there was a noticeable difference in pitch and instrument recognition for the CI group when compared to RH cohorts. However, the CI group matched the RH group for rhythmic discrimination, and excelled in recognizing percussive instruments, whereas non-percussive instruments were harder to distinguish one from another. The authors find that the importance lies in the use of temporal cues for CI users to better distinguish instruments, as proven by their ease in distinguishing rhythm.

A similar study by Stabej and colleagues (2012) also considers the musical perception skills of CI users. The study compared 39 CI-using children and 39 children with RH, and assessed their scores in a MuSIC (Musical Sounds in Cochlear Implants) perception test. The test included comparing rhythms to one another, comparing two melodies with changes in volume, pitch and timbre, and finally subjective testing of instrument identification and emotional response. Results were similar to those found by Innes-Brown and colleagues (2013) in terms of instrument identification being hard for CI users, but with an added difficulty for CI users in associating emotional ratings to instruments. On the other hand, melody differentiation and dissonance rating were equal between CI users and RH participants. The conclusions these researchers wanted to emphasize is simply how music perception is such a broad field that there will always be discrepancies between RH and CI users because of the way music perception is defined. This study chose a broad research subject which, even though it offers different facets of data, does not provide an in-depth look into possible correlations with pitch or timbre specific to the use of CIs.

Chen and colleagues (2010) discuss pitch perception specifically and examine whether musical training can solve this weakness. The comparative study tested 27 children with CIs from varying age groups and with varying levels of music education on a pitch discrimination test - identifying pitch relationships between two tones played in succession, which is higher, and which is lower. It was found that pitch perception capabilities increased alongside students musical training, with participants over 6 years of age performing better than those in preschool. The researchers concluded that this was unrelated with age, but specifically the amount of musical training these children had received from school, since there was no correlation found between pitch perception and age of implantation. Music education, when done with accommodations for CI users, is proven to be extremely beneficial for pitch discrimination.

Overall, we see patterns emerge on which music properties are easy and which are more difficult to perceive for a prelingually deaf child with CIs. Of all elements in musical perception, pitch and instrument recognition (with the absence of timbral cues) are the hardest to discern for children with CIs, when compared to RH children. However, elements such as dissonances and rhythmic cues would be easier, showing no difference between CI users and RH children. Most importantly, we notice that correlations were found between a child's musical perception and their musical training, regardless of whether they were in a CI or RH group. Therefore, the implementation of music education at an early age drastically affects a given child's musical perception in regard to pitch, rhythm and timbre (Chen et al., 2010; Rochette et al., 2014; Torppa & Huotilainen, 2019; Baheux, 2019). As our case-study subject for this paper received early-age music lessons, it is crucial to dive deeper into what this entails for children with CIs, and what kinds of accommodations lead towards effective musical education.

2.1.2 Methods for music education for prelingually deaf children

Based on findings for deaf children learning music with CI, and their general reactions to pitch perception, it has become a common theme to experiment and establish best practices and activities that benefit music education on all levels, despite auditory barriers. Hsiao and Gfeller (2012) aimed to establish these best practices by reviewing eight articles focusing on music instruction in deaf children. Results from each paper are turned into a checklist of recommendations for teachers to establish when teaching deaf students, based on the categories of ear training, singing, piano keyboard, rhythm ensembles and general music appreciation. Most accommodations are anecdotal based on the authors' shared experiences, regarding which activities for each category have proven the most enjoyable for CI users. These accommodations also include a large amount of integration on behalf of parents and their constant support in music lessons. In addition, the use of a heavily percussive instrument such as the piano is recommended over the use of stringed instruments, like the violin.

A similar list of accommodations was proposed by Schraer-Joiner & Prause-Weber (2009), with a special interest in specific facets of music, instead of through the medium of music education and training. Their recommendations are divided in four categories: music detection, discrimination, identification, and comprehension. The authors argue that CI users not only experience each of these facets differently but should have additional resources and strategies to effectively understand them. These recommendations are also anecdotal but focus more on the physical differences that should be considered for CI users, regarding the implant itself. This includes a detailed explanation of the device, and how to aid a child in trouble-shooting their implant if problems occur. The authors also include multiple examples of using rhythm-heavy learning with drums and percussive instruments, with results similar to what was discussed previously in rhythm and timbre perception in young CI users (Innes-Brown et al., 2013).

Similarly, Torppa & Huotilainen (2019) reviewed 21 studies about musical activity for CI users and determined which musical interventions were most successful when compared to RH controls. These recommendations were mostly quantitative when compared to the previous two studies, demonstrating best results from CI users: which musical tasks are easier and which are harder. Recommendations include starting musical training at a young age, using singing as an effective means of learning speech perception, and teaching percussive or plucked string instruments for emphasis on timbral cues. What differentiates this study from others is the focus on musical tasks applied to non-musical development (e.g., using music to help develop regular speech). This helps bridge the gap between music education and general auditory rehabilitation for deaf children, as recommendations for one field are often applicable to the other. Overall, this can help researchers and educators better understand the barriers that CI users face in musical and non-musical aspects of their development. It is also interesting to see once again in this study how the use of the violin as primary learning instrument is not generally recommended to CI users, similar to results shown by Hsiao and Gfeller (2012) above, showcasing once more the exceptionality of our case study's music learning situation.

2.1.3 Musical education improving non-musical development

Continuing from the previous paper, it is important to understand the multi-faceted applications of music education in every part of a CI user's life. Recommendations that apply not only to musical skills but to non-musical development are beneficial to creating an interdisciplinary approach to education, not only for educators but to expose CI users to more options and fields of interest. Baheux (2019) explores this through a case-study of a young CI user and their journey in learning speech, incorporating speech therapy in a musical therapy context, following the student's musical education sessions week-by-week, and noting down the student's progress in speech. The study focuses on techniques to incorporate communication (e.g., between two pianos) and creating abstract concepts such as dialogues and narratives through music. There is also the inclusion of therapeutic musical exercises to help with cognitive load and facilitate learning. Finally, the author uses singing and humming as a method to facilitate vowel pronunciation and create auditory vibrations through the mouth, leading to speech.

In addition to speech rehabilitation, it has been shown that music education can also be applied to helping CI users with general perceptual and cognitive performance. Rochette and colleagues (2014) studied this phenomenon in 14 CI users taking weekly music lessons, and 14 CI users with no intervention. The children were then tested on cognitive exercises regarding their environment: sound identification, scene analysis, and auditory working memory. This was demonstrated through participants association of nature noises to various animals, but also memory tasks akin to finding differences between two schemas or figuring out if there were any modifications present. Students with musical training performed much better in each facet of the experiments, demonstrating how music education might be beneficial to multiple aspects of CI user's development. This kind of research is crucial to help music educators better understand not only child CI users, but how they might develop into adults with CIs, with a minimal number of barriers regarding speech, and memory. Overall, it is established that music education in children with CIs can heavily contribute to developing musical and non-musical abilities in participants, and that these skills will be carried on in their adult lives.

As the case-study subject of this paper underwent surgery for a CI in the right ear at 15 months of age, they also undertook extensive auditory-verbal therapy and musical education for many years. The studies above demonstrate how, through the use of an adapted musical education, there is a correlation between the amount of early-age auditory training and a heightened understanding of rhythm perception, timbre perception and pitch perception (Chen et al., 2010; Rochette et al., 2014; Torppa & Huotilainen, 2019; Baheux, 2019). It would therefore be plausible that, having undergone such early musical training, that the case-study would be more adept at the violin, despite it being a pitch-heavy instrument, and despite there not being many cases of violin-playing musicians with CIs.

2.2 Musical Education in Deaf Adults with CIs

Following children's development, we investigate adolescents (from the age of 15 onwards), young adults and adults with CIs (differentiating prelingual and non-prelingual deafness) and how past music education can improve musical perception results. Studies show that prelingually deaf and non-prelingually deaf adults have a vastly different approach to music perception and understanding of musical qualities such as pitch, timbre, and rhythm. There are also notable differences in learning music as a developing prelingually deaf child, or as a postlingually deaf adolescent / adult with varying degrees of musical education, demonstrating once more how music education at a young age is an important crossover between deafness and musical understanding. These kinds of results and inquiries are relevant to this study, as both prelingual and postlingually deaf CI users have demonstrated similar results in recognition of musical qualities, as long as previous musical education is also similar (Bruns et al., 2016; Moran et al., 2016). Theoretically, this would mean that results from postlingually deaf CI users with similar musical education background to our case study should show similarities in terms of pitch recognition, timbre preference and rhythmic discrimination.

2.2.1 Prelingually deaf and postlingually deaf adults

The first topic for exploration includes the differences in music perception based on whether participants had previously experienced music before deafness, in terms of musical education, playing an instrument, or even just musical listening. Prelingual deafness does not only impede a participant's knowledge of music, but completely alters their ideas and opinions regarding music. Gfeller and colleagues (2012) explore this distinction based on how important music is in the life of CI users through questionnaires, filled out by 31 prelingually deaf CI users about their qualitative perception of the importance of music. Results were compared to previous data on the same subject, but with partially deaf non-CI users. Results showed that over two thirds of CI users still described music as being important in their lives. The author mentions that a majority of these cases were also heavily correlated with these CI-users having a high level of past and present familial involvement in music. Once again, we see early-age musical education as a primary factor in enjoyment and perception of musical qualities.

Another factor that contributes to adult listener's appreciation of music is the distinction between Unilateral and Bilateral implants, or the use of one or two CIs, respectively (Veekmans et al., 2009). The authors gave questionnaires to 23 bilateral CI users, and 23 unilateral CI users (referring to whether participant use one CI or two; one in each ear) in addition to 23 people with RH. Questionnaires were based around music enjoyment and everyday listening habits. Results showed that bilateral CI users enjoyed music listening more than unilateral CI users, but neither reached the level of enjoyment described by people with RH. Feedback was also given as to which timbres and instruments might be more enjoyable than others, especially regarding the use of percussive instruments. All in all, the type of implant and whether the participants had RH were important factors in perception but might also diminish the music appreciation of prelingually deaf CI users. Themes of percussive instrument preference are once again seen, adding to the general understanding that CIs translate music and sounds best when strong timbral cues are present.

Studies comparing postlingual and prelingual deafness and their effects on musical listening are not very widespread, but the research seen in the field highlights how there might not be as many differences between both groups as we might think in terms of perception of musical qualities. Moran and colleagues (2016) explored musical and timbral enjoyment in cohorts of prelingually and postlingually deaf CI using adults, with the specific purpose of comparing the two. Participants were asked to rate their enjoyment and subjective description of various instruments and timbres, rating qualifiers such as "tininess", "richness", "pleasantness" and "naturalness" of sound from 0-10. Results showed lots of similarities between both groups, especially for the later two qualifiers for pleasant and natural instrument sounds - in other words, prelingually deaf CI users and postlingually deaf CI users demonstrate equivalent timbre preference and timbre recognition. This opens the discussion for how similarities exist between postlingually and prelingually deaf CI users' music perception, and how research within one cohort's music recognition skills could inform the others.

Continuing into this inquiry, Bruns and colleagues (2016) dive into specific comparisons between rhythm, melody, harmony, and instrument recognition between postlingually deaf and prelingually deaf CI users. They were surprised to find that test results between both CI user groups (compared to RH participants as well) showed only marginal differences, with the only test showing significant but still minute differences being the chord / harmony discrimination test. Postlingually deaf and prelingually deaf cohorts demonstrated similar rhythmic discrimination, instrument recognition and melodic matching skills with each other, once more suggesting that results pertaining to these musical qualities (pitch, timbre, and rhythm) would be similar between all CI users, regardless of year of implantation and age of deafness.

As the topic of postlingually deaf adults and teenagers with CIs has been researched mostly exclusively from prelingually deaf counterparts, these studies open up the possibilities of similarities between results, and how the musical recognition abilities of one cohort could inform the others. This is crucial for our case study, as there exist many studies of postlingually deaf adults with CIs, but not many of prelingually deaf adults who grew up using CIs, as CI implantation for prelingually deaf children were only done in the late 1990s, making them adults only now. As our case-study violinist is now a young adult, it is worthwhile in seeing how musical recognition abilities are developed in adult CI users, with a wider range in musical experience, education and even music-playing, by examining data from postlingually deaf musician adults with CIs.

2.2.2 Music perception in adolescents / young adults with CIs

Music perception in deaf adolescents is similar to that of deaf children, with the distinct difference of the individual's background and lived experiences. Vongpaisal and colleagues (2006) studied how deaf children and adolescents / young adults compare in terms of song recognition capabilities, and consequently pitch recognition. The experiment was split in four experiments: identifying popular songs in instrumental, vocal, and synthesized versions, detecting pitch changes in repeating tone contexts, and more subtle pitch changes in melodies. Results were compared between age groups, and it was found that generally adolescents performed better than children in terms of melody recognition especially by pop songs with lyrics. It is believed that children might have more difficulty recognizing these songs based on lack of listening experience. Vongpaisal and colleagues proposed hypotheses relating to children having higher brain plasticity, and therefore being better at recognizing small pitch changes, however there was no distinguishable difference in these experiments between deaf children and deaf adolescents.

Continuing on with pitch perception, many researchers interest themselves not only in music perception or importance, but how music links to activities in everyday life. Similarly to Looi and She (2010), it has been established that music can be a very enjoyable experience for CI users, under the right circumstances (Gfeller et al., 2019a). The study is comprised of 40 adolescent / adult CI users answering a questionnaire pertaining to their music education, and music appreciation. Again, similarly to Looi and She (2010), the questionnaires were also open-ended to ensure participants can include what the preferred methods of music listening might be, to establish best practice in a listening environment. These preferred methods also revealed that 75% of participants would be interested in furthering their music education in order to have a better appreciation of music, showing how important music education can be even for the casual listener.

Following with the idea of brain plasticity, the stage of adolescence is also believed to be critical in a person's brain development (Petersen et al., 2015). The study uses electroencephalography (EEG) to measure brain responses to changes in musical features, between adolescents with CIs and RH adolescents. The goal was specifically to capture mismatch negativity (MMN), a sensory recognition in this case to deviations in music such as timbre, intensity, rhythm, and pitch. Researchers found that all these features elicited strong brain reactions, except for pitch in CI users. In addition, the amplitude of MMNs were significantly smaller in CI users than RH adolescent, suggesting a poorer music discrimination ability.

Linking to brain development in adolescents, studies were carried out specifically on young adolescents' music perception of different instruments (Kim et al., 2015). Adolescent CI users were given musical samples of songs played on four different Western instruments, and five traditional Korean instruments, and were asked to identify each instrument along with their subjective ratings on appreciation of timbre. Results were also compared with those of RH adolescents. Similar to previous studies, the CI group had a relative lower score in instrument recognition when compared to RH listeners. However, CI adolescent were very strong at recognizing percussive instruments with strong attacks, also as seen by Innes-Brown and colleagues (2013). These instruments included two traditional Korean plucked string instruments, and one Korean instrument with strings and bow, similar to the traditional violin / fiddle. This could prove useful in further studies for CI users hearing or playing stringed instruments, similarly to our case-study.

Overall, we notice that pitch perception, timbre preference and melodic/rhythmic discrimination are important musical qualities that have been seen to be captured differently by a CI when compared to the RH ear and captured differently based on a postlingual or prelingual CI user's experience with music listening or playing. A CI user's musical education also seems crucial to their experience in musical understanding and pleasure, and by consequent, their abilities to better identify the musical qualities that are the topic of this investigation.

2.3 Research Questions and Hypothesis

This case study will discuss how a university-level violinist with a CI perceives music differently (regarding pitch perception, timbre preference and melodic discrimination, topics that have all been studied as being harder to perceive by CI users), while still achieving the same university-level of musicianship as their violin-playing RH peers. There is a large gap in research regarding CI users playing violin, as explained by its reliance on heavy pitch precision, when compared to other instruments, and even more so for CI violinists reaching an advanced level in music (Schraer-Joiner & Prause-Weber, 2009; Hsiao & Gfeller, 2012). Therefore, this study will focus specifically on pitch discrimination and pitch matching, based on previous research done on CI users having difficulty with pitch perception (Innes-Brown et al., 2013; Wang et al., 2011; Petersen et al., 2015; Stabej et al., 2012). We want to investigate how musicianship compares between a high-level deaf violinist with CI and other violinists with RH, using pitch discrimination tests.

The case study will consist of a participant with prelingual deafness in both ears, but with minimal residual hearing in the left ear. The participant uses a unilateral CI in the right ear, and a hearing aid in the left. The effect of the participant's residual hearing and use of a hearing aid was noted early on by their audiologist as not being significant in terms of the participant's hearing experience - they predominantly rely on their unilateral CI (Saunders, 2021). In addition, the participant has between 10-12 years of musical training on the violin and is currently at a university-level in musicianship.

Research has shown that musicians with CIs can still perceive rhythm and timbre to a comparable extent to RH Musicians (Kim et al., 2015; Vongpaisal & Managhan, 2014; Innes-Brown et al., 2013). As for pitch, research shows that CI users have more difficulty with melodic pitch discrimination when compared to RH musicians (Innes-Brown et al., 2013; Wang et al., 2011; Petersen et al., 2015; Stabej et al., 2012), but we want to compare if this holds true with a CI user who has mastered the violin. Our study will try to answer **to what extent would our case-study participant perceive musical pitch, rhythm and timbre when compared to other violin-playing RH counterparts, or other CI users.** Since it has already been established that our case-study CI user has undergone musical training at a young age and reached an unprecedented musical level on a pitch-heavy instrument despite their deafness, the given hypothesis would be that they would demonstrate higher than expected pitch perception for a CI user and would therefore compare more closely to RH counterparts. It would also be assumed that their musical rhythm and timbre perception would still be quite high, and equally comparable to RH counterparts.

3. Methodology

The study is quantitative by design, as it features three tests to relate numerical values with participants' musical abilities related to pitch perception, timbre preference, and melodic discrimination. Non-manipulated independent variables are the musicians' hearing abilities (CI or RH, as participants are chosen on this variable), the musicians' main instrument (the violin) and level of musicianship (roughly, university-level, with 10-12 years of experience). Dependent variables include pitch matching, timbre preference, and melodic discrimination (in pitch and rhythm).

The following sections include all details on participant recruitment, instrumentation used for data collection and primary details on the test being administered to the CI study participant, as well as the RH comparison group.

3.1 Participants

The case-study focuses on a critical case participant, while comparing their results to a non-random sample of participants. This study is observational; the participants do not undergo a music intervention, but rather are chosen based on previous music experience and auditory capabilities (comparing RH violinists to a deaf violinist with CIs).

3.1.1 Study Participant

The study participant of the critical-case study is an advanced violinist with a CI. For the purposes of this study, this participant will be referred to as *Leo (he/him)*. Leo is a 19-year-old violin student in the third year of his bachelor's in science and music, at the University of Ottawa. He was diagnosed with profound hearing loss at two months of age, and subsequently received hearing aid (in his left ear, at six months of age) and a CI (in his right ear, at fifteen months of age). Although he has residual hearing in his left ear, it has been determined by Leo and his audiologists that he predominantly uses the CI in terms of receiving auditory input, and that his non-implanted ear does not contribute to the way he experiences music. What makes this case unique is a CI user learning and excelling at a pitch-heavy instrument, the violin, instead of more widely researched instruments such as the piano or percussions. In a study conducted by Saunders (2021) on the same case-study, she was able to pinpoint three major themes within the interviews led that might explain this proficiency in violin playing: the early emergence of interest and skill in music as supported by the family, the CIs capabilities to best capture pitches well within the violin's regular range, and the use of accommodating techniques to improve musicianship.

The first theme relates mostly to Leo's background in learning music with familial support. As Gfeller and colleagues (2012) demonstrated, a high level of familial involvement in music leads to a drastic rise in interest and the importance of music in the lives of deaf children or adolescents. A sister-study by Saunders (2021) uses questionnaires and interviews with Leo's family to inquire how music was not only encouraged, but Leo's level of auditory ability was never put into question. This concretely helped Leo subconsciously break through social barriers normally experienced by CI users and fueled his persistence to achieve a remarkable level in music playing.

The second theme is more of an observation by Saunders (2021), detailing how coincidently, the violin's regular playing range fits semi-perfectly within an effective range for a CI to capture - within C4 (~260Hz) and G6 (~1560 Hz). This observation lies in the CI's purpose in being most effective in capturing frequencies mimicking the human voice (between 200Hz and 4000Hz), and the violin also being an instrument within the range of the human voice (Limb & Roy, 2014). Similar themes relating to the violin's timbre being easy to interpret by the CI were also observed, similar to what was described by Kim and colleagues (2015). Saunders describes that other than pitch and timbre, rhythm perception was described very positively, as seen in multiple reports testing CI users' sense of rhythm.

The final theme developed by Saunders is a comprehensive summary of accommodations and techniques used by the participant to work through difficulties present in music playing when using a CI. The most useful technique to the participant was described as "hearing inside"; a vibrotactile feedback technique comprised of feeling the vibrations from the violin with the hands and face, alongside the sound being translated through electrical patterns in a CI. This technique has appeared in multiple case studies (Cheng, 2018; Gfeller et al., 2019b) as described by Saunders (2021), and often lead to better musical memory, imagination and cognitive conceptions that go hand-in-hand with music perception.

Saunders (2021) outlines the exceptional musical skill of the participant using CIs, and the way the participant's past experiences are highlighted as pillars of this skill. The implications are important for a new generation of pediatric implantees in regard to opportunities they might have in music that were previously left unexplored. What these themes do not cover however, is just how well Leo's musical capabilities might compare to another violin student with RH. It is believed that Leo's pitch recognition might be above the average for CI users, as demonstrated by his mastery of a pitch-dependent instrument.

3.1.2 Comparison Group

In this study, Leo's pitch recognition, timbre preference and melodic discrimination skills (regarding pitch and rhythm) will be quantitively compared to RH peers. The goal of comparison is to see whether Leo's musical perception skills are comparable to RH peers, as they all meet a similar standard in violin-playing.

Participant recruitment is based on matching control RH participants to Leo's violin education. Sampling is non-randomized, as the music level and ability of RH participants is a required variable for recruitment which was done principally through posters at the University of Ottawa, and by word-of-mouth between classmates, violin players and teachers. The recruitment poster is included in Appendix 1 for reference (see Supplementary Material 1).

We recruited 6 RH participants to create a sample size at which to compare with our one CI case-study. 3 participants were current university students (2 in fourth year undergraduate in music as violin instrument majors, 1 in graduate studies in music, having previously studied been a viola major in undergraduate studies). Of the other 3 participants, 2 were recent graduates (within 3 years of graduation) of undergraduate studies in music with violin or viola as an instrument major, and 1 was a recent high-school graduate, having achieved a high-level of violin playing and being accepted for an audition for the violin, for undergraduate studies in music at the University of Ottawa. It was established that both the viola and violin would necessitate comparable music-playing abilities due to their similarity in size and shape, and physical method of playing, and would therefore be comparable instruments. Participants were asked standard demographic information, and were not to be excluded based on sex, gender, race, culture or general ability (other than the presence of any kind of hearing impairment or prior damage to the ear / eardrum, or not matching the required musical ability in violin as required). Participants were not paid for their participation, and the total experiment time is believed to be short enough (roughly one hour for each participant) as to not discourage volunteers.

3.2 Measurements and Instrumentation

For this study, musicianship is understood to include pitch perception, timbre preference and melodic discrimination. Three quantifiable tests were therefore established to measure these aspects of musicianship.

Test 1 was intended to mimic pitch recognition and matching on a violin. While the purpose of the test was to interpret a participant's perception of pitch, the quantitative measure of pitch was done through frequency (in units of Hertz, Hz). Using a digital slider (Hutchins & Peretz, 2012) that changes frequencies as one slides their finger on it (similarly to a violin string, see Supplementary Material 2, Appendix 1), participants were asked to locate and reproduce a digital tone played from a computer stereo. The slider is very sensitive, encouraging participants to be as precise as possible when trying to match the heard pitch to the slider's frequency. Participants were each given the time and opportunity to try out the slider with a test frequency. The measurement taken was the numerical difference between the initial pitch's frequency, and the participant's interpretative pitch frequency on the slider. As measurements were taken by the frequency slider at every 1/25th of a second, a 2-second window was attributed to data collection, which is then considered for its average and standard deviation as a participant's given answer.

Test 2 was a timbre preference test, developed by Edwin E. Gordon (1990;1991). This test was intended as a subjective preference test between midi recordings, meant to represent various instrument timbres and aural range. The test's midi recordings use synthesized tone colours and octave ranges to mimic instrument timbres, without presenting the actual instrument timbres themselves in order to ensure an accurate, unbiased assessment of timbre preference, independently of participants' previously known preference in instruments (Gordon, 2008). Categories included seven groupings consisting of a variety of brass, woodwind, and string instruments, also grouped by the pitch range of the recording. Participants were asked to listen to the same short melody, played twice by two different instrument categories, and to choose which recording is subjectively most pleasant to listen to, or which sounds best. The participants' preferences were compiled, and each given instrumental group was ranked in order of most to least preferred timbre range.

Test 3 was an Advanced Measures of Music Audiation (AMMA) test, also developed by Edwin E. Gordon (1990;1991). This online self-scoring test yields general music aptitudes relating to tones, rhythms, and their combination. This test was also used as generalized background information relating to each participant to establish a threshold of music ability in each participant. The test considers two variables as part of a melodic discrimination coefficient, through recognition of pitch and/or rhythmic changes. Participants were asked to listen to two recordings of a melody, and to determine whether both recordings are identical or different. If they are different, it would represent exclusively a difference in pitch, or in rhythm, and the participant was asked which they believe it to be. Their overall resulting audiation scores are a composite score of melodic pitch and melodic rhythm discrimination between the recordings, and how successful participants were in each category. It is expected that there might be overlap in results between this test's melodic discrimination in pitch, and the pitch perception results of Test 1; the case-study's performance in one test, whether positive or not in pitch perception, should be equally reflected in the other.

Test 1 has been proven reliable for previous pitch recognition test with the Université de Montréal by the frequency slider's creators, through Test-retest reliability (Hutchins & Peretz, 2012). Validity of data is be tested through triangulation and correlations found between pitch discrimination in participants between Test 1 and Test 3. Test 2 and Test 3 have been validated through many studies with the University of South Carolina (Gordon, 1990;1991), and by other researchers in the field such as Schleuter (1993) and Fullen (1993).

All tests were administered on the same computer in the University of Ottawa Piano Pedagogy Research Laboratory. The research environment was a closed room at the Piano Pedagogy Research Laboratory, and listening volume of tests were set to a comfortable level for all participants. Participants were allowed breaks in between tests (if needed) in the event that a test is too lengthy and physically or mentally draining. Participants were asked about previous musical training to check if they have any relevant experience that might set them apart from the rest of the control group in terms of exceptional pitch recognition abilities. Participants and data collection was approved by the University of Ottawa's Social Sciences and Humanities Research Ethics Board (REB).

3.3 Data Collection

Data collection on the quantitative side of the experiment is taken directly from the three tests mentioned above, with each test collecting different kinds of datasets.

Test 1 focuses mostly on distance in Hz between a heard target frequency and a recreated frequency on a digital slider (as well as precision and standard deviation of answers). The gap in frequency between pitches can be correlated to a high or a low level of pitch recognition accuracy. It is hypothesized that to play a pitch-heavy instrument such as the violin, a musician would need a certain high-level of pitch accuracy and precision, as there are no physical landmarks on the instrument to distinguish pitch (e.g., frets on a guitar, piano keys, etc.). Data collection from RH hearing participants informs whether this hypothesis is true and might merit further research comparing a violinist's pitch recognition to another musician's on a different instrument.

Pitch is often identified as a difficult musical quality to discern by electrical signals of the CI (Innes-Brown et al., 2013; Wang et al., 2011; Petersen et al., 2015; Stabej et al., 2012; Deroche et al., 2014), specifically in terms of high pitch precision and fidelity. CI technology is built to best identify and hear frequencies and pitch within the range of the human voice (most effective from ~300Hz to ~4000Hz) for the purposes of communication, with each individual's perception of pitch outside these frequencies varying from mediocre to extremely difficult in recognition (Limb & Roy, 2014). Therefore, for the purposes of this test, 10 target pitches were chosen centered around 440Hz, with the lowest target frequency at 261.6Hz, and the highest at 783.9Hz.

The pitch recognition test challenges participants' capacities to identify, remember and match a pitch to the best of their abilities. Data was captured and recorded on a physical frequency slider and by screen recording of each participant's attempts (Hutchins & Peretz, 2012). Each participant was asked to take the time needed to find the pitch they believe to be closest to a target pitch heard beforehand. Once they were satisfied with their answer, participants were asked to attempt to keep their finger still on the frequency slider for at least 2 seconds. This has two purposes: to examine a participant's window of precision of a given frequency, and to collect an average answer, given the slider's extremely precise input.

The slider's software captures 25 data points per second, resulting in 50 data points for the final 2 seconds taken from each participants' recorded answers. These points are then compared to the target pitch on a graph, in order to evaluate closeness of pitch reached by each participant, in addition to the standard deviation of a participant's answers within those 2 seconds.

Closeness of pitch represents the accuracy of a perceived pitch answer compared to the target pitch and is determined based on how close a given participant's (CI or RH) pinpointed frequency is to the target frequency. It is important to note that the measure of frequency is an exponential function of perceived pitch, and therefore frequencies will be converted to cents (1 semitone = 100 cents). Just-noticeable difference (JHD) represents the smallest threshold at which a change in frequency is perceived and evaluated for the RH ear (Kollmeier et al., 2008). Target frequencies (Suits, 1998) and their related JHD are included in Table 1 (see Appendix 1). A low JHD between frequency answers represents high pitch perception, and vice-versa. For the purposes of data analysis, a satisfactory closeness of pitch is determined as a difference of under 50 cents (or half a semitone), a good closeness of pitch is represented by a difference of under 25 cents (noted as the JHD of perceived frequency for RH non-musicians) and an exceedingly positive result constitutes any difference of under 12 cents (noted as the JHD of perceived frequency for RH musicians) (Hutchins & Peretz, 2012; Geringer & Worthy, 1999; Peretz & Hyde, 2003; Kollmeier et al., 2008). Closeness of target pitch is measured in absolute values of how far participant's answers are from the target pitch (regardless of whether answers fall above or below the target pitch) whereas closeness of pitch between RH participants and the CI study participants depends on data as it is measured, taking into account how far answers are from each other.

Precision of pitch perception is determined by the standard deviation of a given participants window of frequency answers, on the slider. A small standard deviation represents a very accurate response, and vice-versa. It is important to note that whether a participant's perceived pitch is close to the target pitch is irrelevant in terms of the precision of their answers.

Test 2 is a subjective inquiry into what timbres sound better to a participant, purely by personal preference. The main assumptions for results include that violin-playing participants overall would enjoy and prefer the timbre of the violin or strings. Data will then, similarly to Test 1, be compared between RH participant and the CI user.

Timbre is the musical attribute associated with instrument sound preference and discrimination and has been targeted as a primary vulnerability in terms of CI music listening. CI users have identified certain instruments and timbres as being more enjoyable and recognizable based on factors such as the instruments rapidity of attack and percussiveness (Kim et al., 2015) or how natural the instrument's timbre was, opting for woodwinds instead of brass instruments with metallic, tinny timbres (Moran et al., 2016). As this study is specifically looking into violin-playing participants, we also wanted to examine whether the timbre of strings would be more pleasant to the group, overall.

Test 3 provides a threshold of music ability at which we can evaluate all participants equally. It is a basic assumption for the study that all participants roughly have the same level of music education and music ability based on their self-reporting, and it is hypothesized that results from the AMMA test will be similar between RH participants and the CI user. Since the AMMA test incapsulates both tonal pitch and rhythmic components, it is also hypothesized that the CI participant would perform best with rhythmic perception, as opposed to pitch perception, based on past literature (Innes-Brown et al., 2013; Wang et al., 2011; Petersen et al., 2015; Stabej et al., 2012; Deroche et al., 2014). This is for the same reasons discussed above for Test 1, regarding the CI's pitch recognition technology.

The Advanced Measures in Music Audiation (AMMA) test is designed as a method of testing a given music student's aptitude in tonal and rhythmic discrimination ability (Gordon, 1991). The purpose of the test is not only to derive separate tonal and rhythmic aptitude scores from how many correct answers a student has on the test, but also to compare the scores with a database of musical and non-musical students all over the United States in order to establish percentile ranks and demonstrate which students would excel most in musical studies based on these aptitudes. Students are given 30 questions, scoring marks for every question answered correctly, 10 of which with a tonal difference (category T), 10 with a rhythmic difference (category R), and the last 10 being the same in melody and rhythm (category S). The 30 questions had a random distribution of T, R and S. If a category S question with two identical prompts is answered correctly, it is scored as a correct mark for both tonal and rhythmic discrimination. One point is also taken away from the appropriate category for an incorrect answer. In addition, every correct answer for one category (T or R) is also a correct answer for the opposite category (for example, correctly recognizing a tonal difference implies also correctly knowing that there is no rhythmic difference present) meaning the total possible score is of 40 correct marks for each test (20R, 20T).

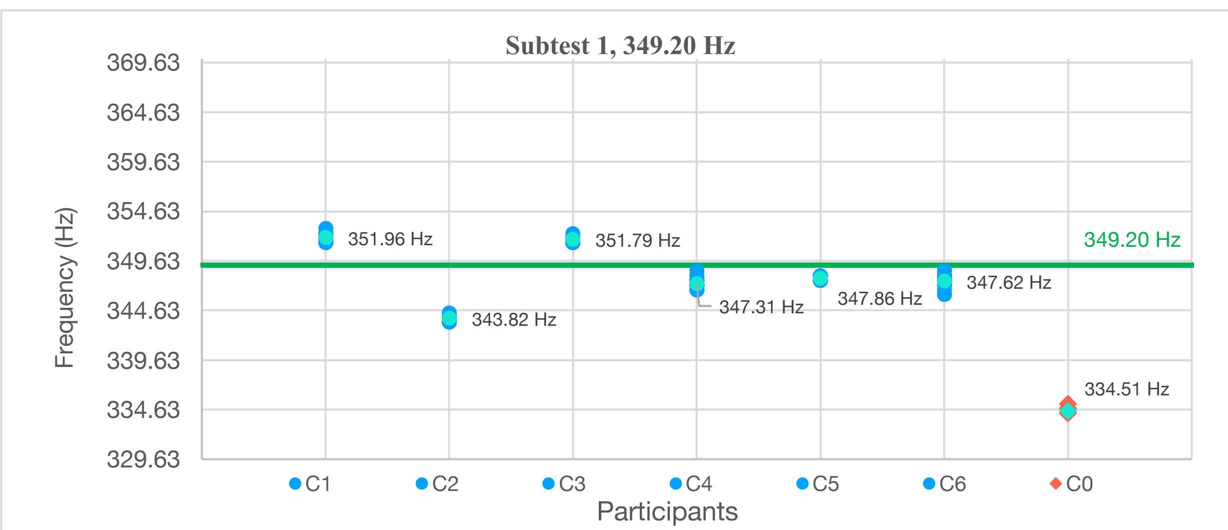
Percentile ranks are used to identify excellent musical aptitudes within students, as well as identify non-musical student as compared to the survey of undergraduate students tested previously (Gordon, 1991). A composite percentile rank between 20^{th} and 89^{th} percentile is considered as the standard score for an undergraduate music student, in terms of performance of tonal and rhythmic aptitudes. A percentile rank over the 90^{th} percentile demonstrates excellent audiation abilities, as compared to peer data collection, exemplifying high-achieving music students, or non-musical students that may have a high potential in musical studies. Percentiles are extracted as both individual ranks in tonal and rhythmic audiation ability, and as a composite score taken from the total correct answers.

4. Results and Analysis

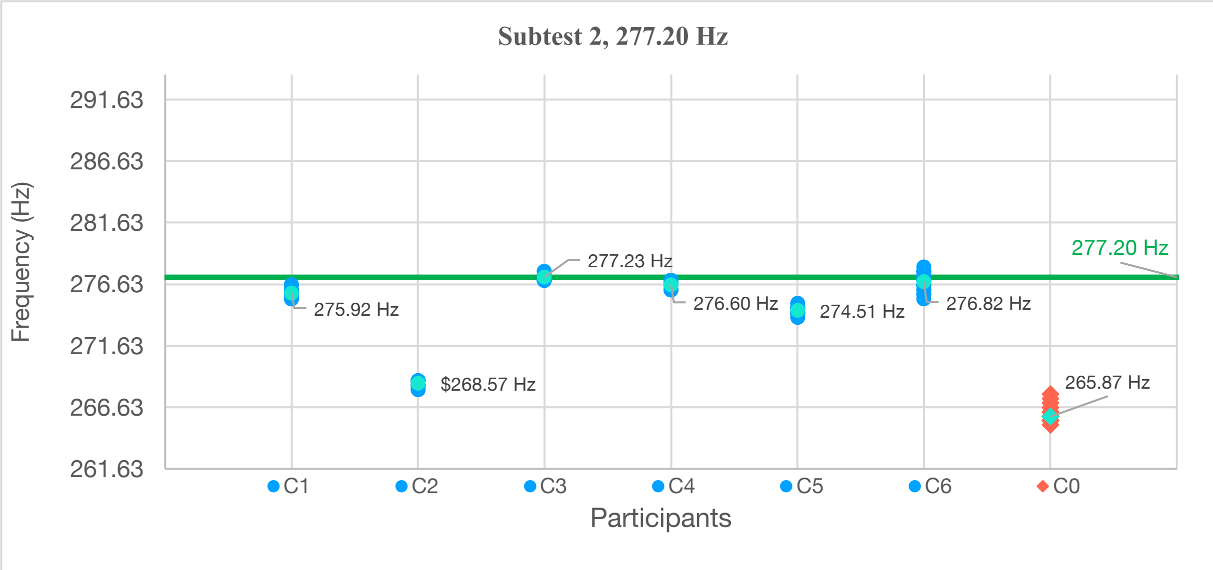
This case-study is built as a comparative critical-case observation, and result analysis focuses on comparisons between RH participants and the exceptional CI user. RH participant data is used to create an average dataset for pitch recognition in terms of average-RH closeness of pitch-matching, average-RH precision and standard deviation of pitch envelope, and average-RH AMMA test results, as compared to the AMMA percentile rank dataset (Gordon, 1991). Error bars are calculated as well for variability between participants, either in the form of bar graphs or line charts for multiple points. Leo's results placed on these same graphs demonstrate the clear comparison between the CI user and the RH participants through standard error, variance, and general standard deviation comparison of data points.

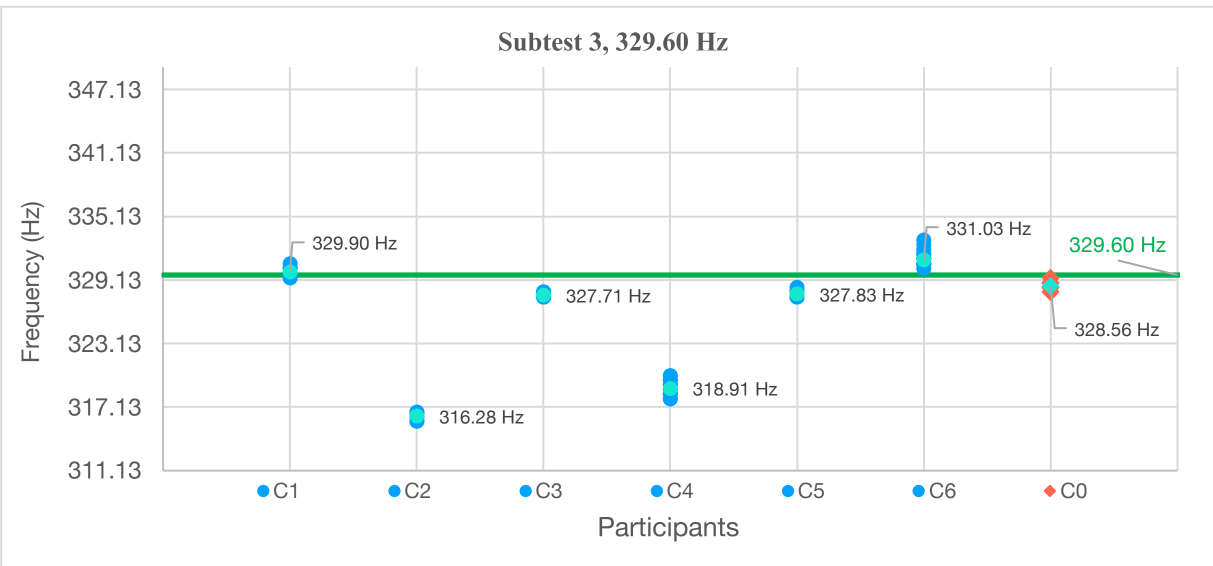
4.1 Test 1 Results - Pitch Recognition

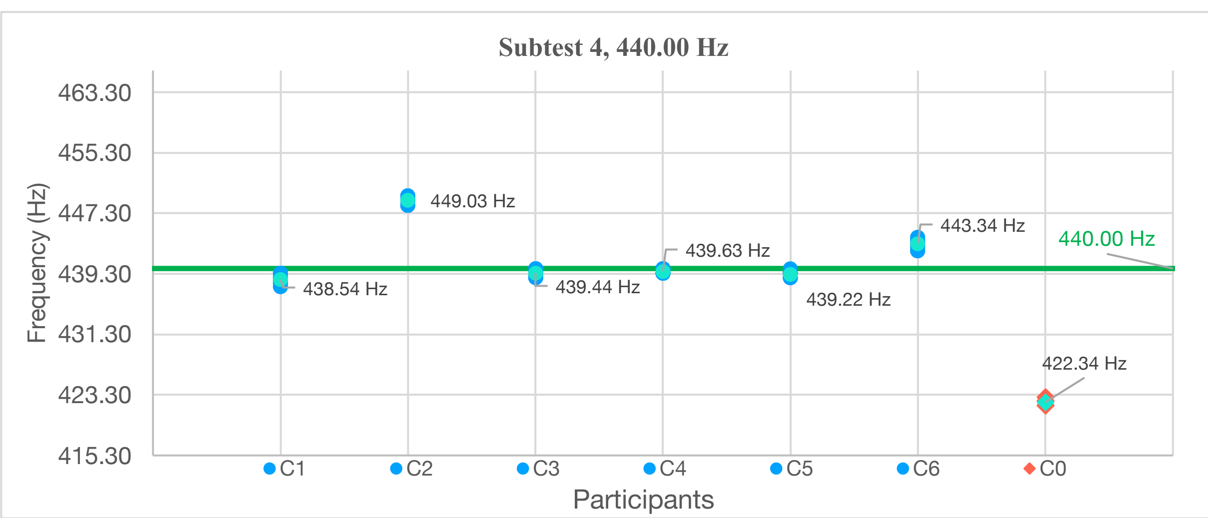
Participants' results are seen in Graphs 1-10 (see below) with notable and average closeness of pitch and precision of perceived pitch shown in Table 2 (see below). The study participant succeeded in a satisfactory closeness of pitch to the target on over half of the subtests, with 60% success rate with less than 50 cents of difference in pitch.

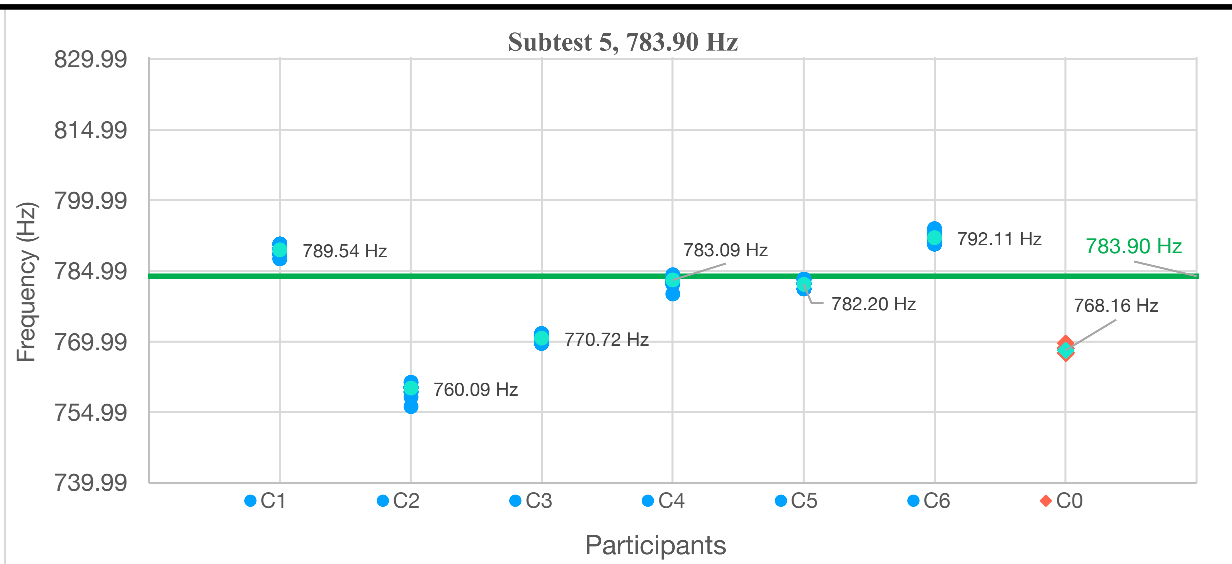


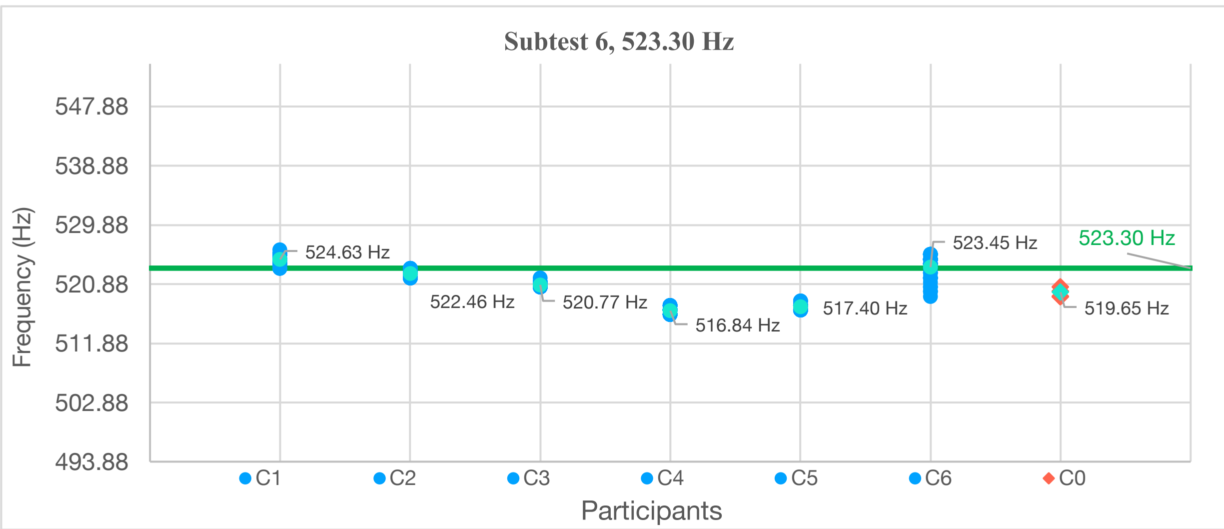
Subtests 1-10 (as seen above and below). Results of the pitch matching recognition test (Test 1) for all 10 subtests of 10 different pitch values to match, in Hz. Target pitch is shown in green, with scatter points of participants' answers (with the CI study participant on the right, marked as "C0"), and average pitch answers tagged.

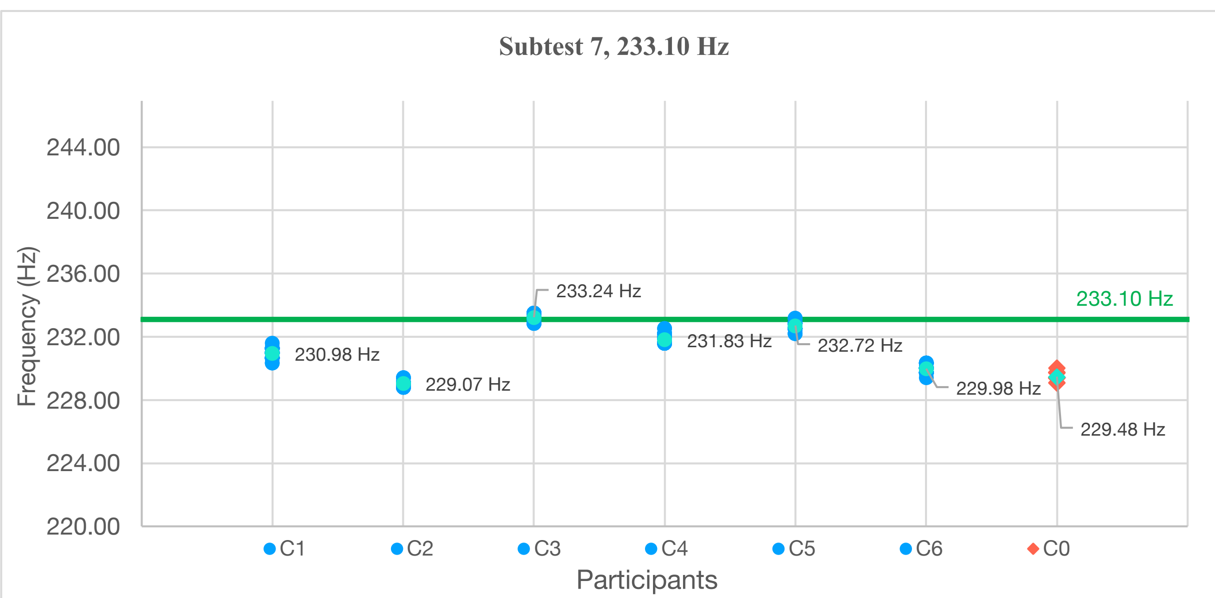

Subtest 2, 277.20 Hz
Frequency (Hz)
291.63
286.63
281.63
276.63
271.63
266.63
261.63
277.23 Hz
275.92 Hz
276.60 Hz
274.51 Hz
276.82 Hz
277.20 Hz
$268.57 Hz
265.87 Hz
C1
C2
C3
C4
C5
C6
C0
Participants

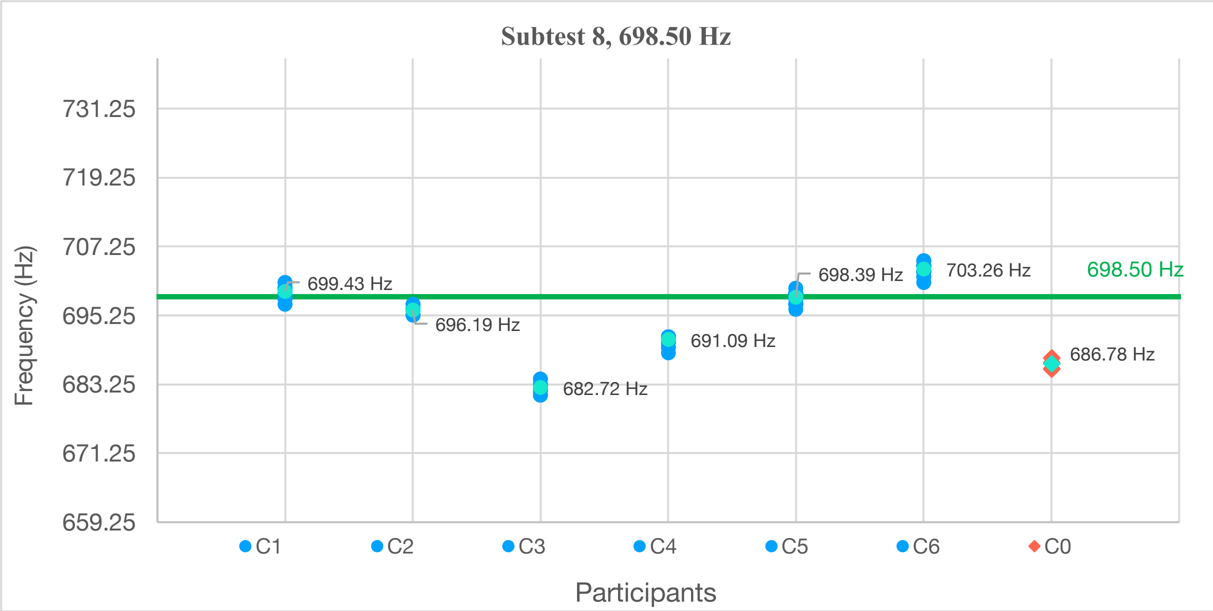

Subtest 3, 329.60 Hz
Frequency (Hz)
347.13
341.13
335.13
329.13
323.13
317.13
311.13
329.90 Hz
331.03 Hz
329.60 Hz
327.71 Hz
327.83 Hz
328.56 Hz
318.91 Hz
316.28 Hz
C1
C2
C3
C4
C5
C6
C0
Participants


Subtest 4, 440.00 Hz
Frequency (Hz)
463.30
455.30
447.30
439.30
431.30
423.30
415.30
449.03 Hz
443.34 Hz
440.00 Hz
439.63 Hz
438.54 Hz
439.44 Hz
439.22 Hz
422.34 Hz
C1
C2
C3
C4
C5
C6
C0
Participants

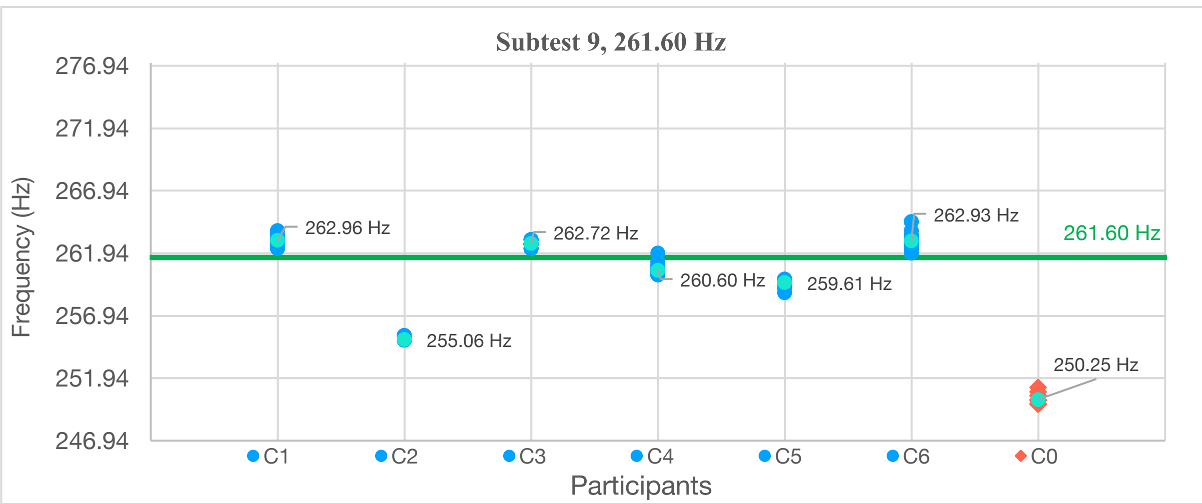

Subtest 5, 783.90 Hz
829.99
814.99
799.99
784.99
769.99
754.99
739.99
Frequency (Hz)
789.54 Hz
760.09 Hz
770.72 Hz
783.09 Hz
782.20 Hz
792.11 Hz
783.90 Hz
768.16 Hz
C1
C2
C3
C4
C5
C6
C0
Participants


Subtest 6, 523.30 Hz
547.88
538.88
529.88
520.88
511.88
502.88
493.88
Frequency (Hz)
524.63 Hz
522.46 Hz
520.77 Hz
516.84 Hz
517.40 Hz
523.45 Hz
523.30 Hz
519.65 Hz
C1
C2
C3
C4
C5
C6
C0
Participants

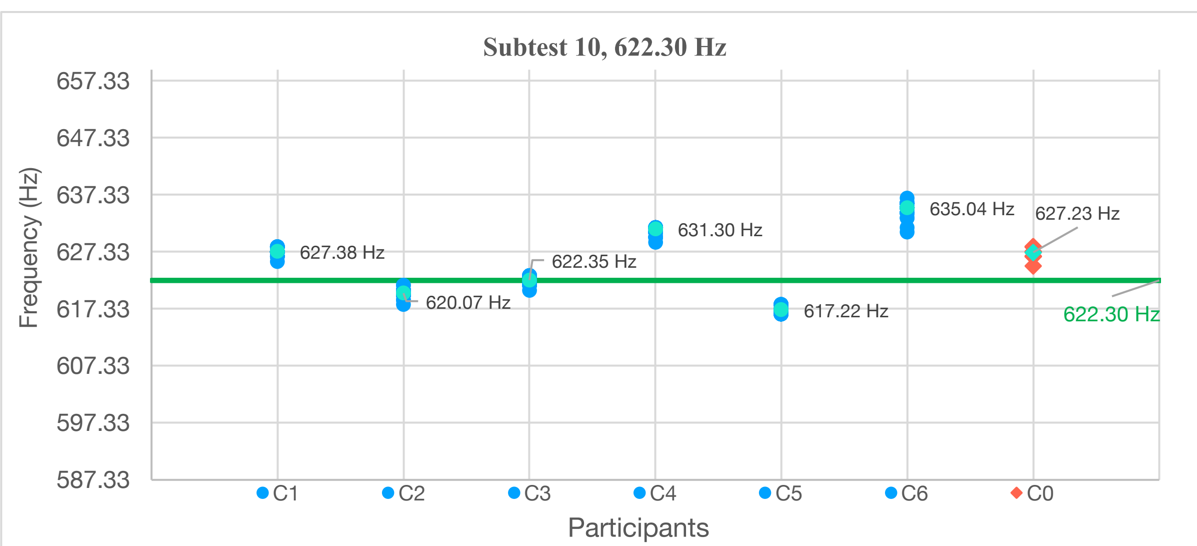

Subtest 7, 233.10 Hz
244.00
240.00
236.00
232.00
228.00
224.00
220.00
Frequency (Hz)
230.98 Hz
229.07 Hz
233.24 Hz
231.83 Hz
232.72 Hz
229.98 Hz
233.10 Hz
229.48 Hz
C1
C2
C3
C4
C5
C6
C0
Participants



Subtest 8, 698.50 Hz
731.25
719.25
707.25
695.25
683.25
671.25
659.25
Frequency (Hz)
699.43 Hz
696.19 Hz
682.72 Hz
691.09 Hz
698.39 Hz
703.26 Hz
698.50 Hz
686.78 Hz
C1
C2
C3
C4
C5
C6
C0
Participants



Subtest 9, 261.60 Hz
276.94
271.94
266.94
261.94
256.94
251.94
246.94
Frequency (Hz)
262.96 Hz
262.72 Hz
262.93 Hz
261.60 Hz
260.60 Hz
259.61 Hz
255.06 Hz
250.25 Hz
C1
C2
C3
C4
C5
C6
C0
Participants



Subtest 10, 622.30 Hz
657.33
647.33
637.33
627.33
617.33
607.33
597.33
587.33
Frequency (Hz)
635.04 Hz
627.23 Hz
631.30 Hz
627.38 Hz
622.35 Hz
620.07 Hz
617.22 Hz
622.30 Hz
C1
C2
C3
C4
C5
C6
C0
Participants

When compared to RH JHD, the study participant obtained a success rate of 30% for less than 25 cents of difference, and 10% for less than 12 cents of difference of pitch. In these same categories respectively, the RH average success rates were of 93% accuracy for less than 50 cents, 82% accuracy at less than 25 cents, and 57% accuracy at less than 12 cents of difference of pitch. The study participant's average closeness of pitch overall was 38.29 cents, still falling within the satisfactory closeness under one semitone (50 cents). The study participant's most successful target pitches identified were 523.3 Hz and 622.3 Hz, while also proving more successful with pitches above these frequencies, when compared to all those under 523.3 Hz. It is also important to note that success rates are based off averages of the study group, and that there are many instances of the study participant performing a better closeness of pitch than singular given RH participants.

Participant	*Av. Closeness of Pitch in cents*	*Av. precision*
C1	8.90	0.50
C2	30.43	0.37
C3	15.15	0.37
C4	15.80	0.45
C5	8.70	0.39
C6	14.82	0.77
C0	38.29	0.37
AVERAGE RH	15.63	0.48

Table 2. Pitch matching perception test (Test 1) results. Results are taken as average in pitch closeness and average in precision of answers, through all 10 subtests. CI study participants marked as "C0", and a total average of the comparison group is included at the bottom.

The study participant's closeness to the RH comparison group overall was more successful, with his answers falling within 12 cents of the comparison group on 20% of subtests, and within 25 cents or 50 cents of the comparison group both on 60% of subtests. In addition to this, the study participant landed within a standard error of the comparison group average (based on the RH group answers' standard deviation) on 40% of all subtests.

In terms of precision of pitch perception, the study participant attained an average standard deviation in answers of 0.36607, while the RH comparison group attained an average standard deviation of 0.47547. The study participant attained a higher precision of pitch on 90% of subtests when compared to the RH comparison group, demonstrating overall a very high precision in pitch precision.

4.2 Test 2 Results - Timbre Preference

As the test is more subjective in nature, results are presented as the number of votes attributed to a specific timbre grouping for each participant. The groupings in question were determined by similarity of timbre and chromatic octave ranges of instruments. These timbre groupings include instrument example such as the flute / violin as a highest-octave grouping, clarinet / viola as a mid-range octave grouping, and tuba / sousaphone / string bass as a lowest-octave range grouping, among others. Participants results were aggregated together based on the score provided for each grouping, in hopes of finding most and least preferred timbres.

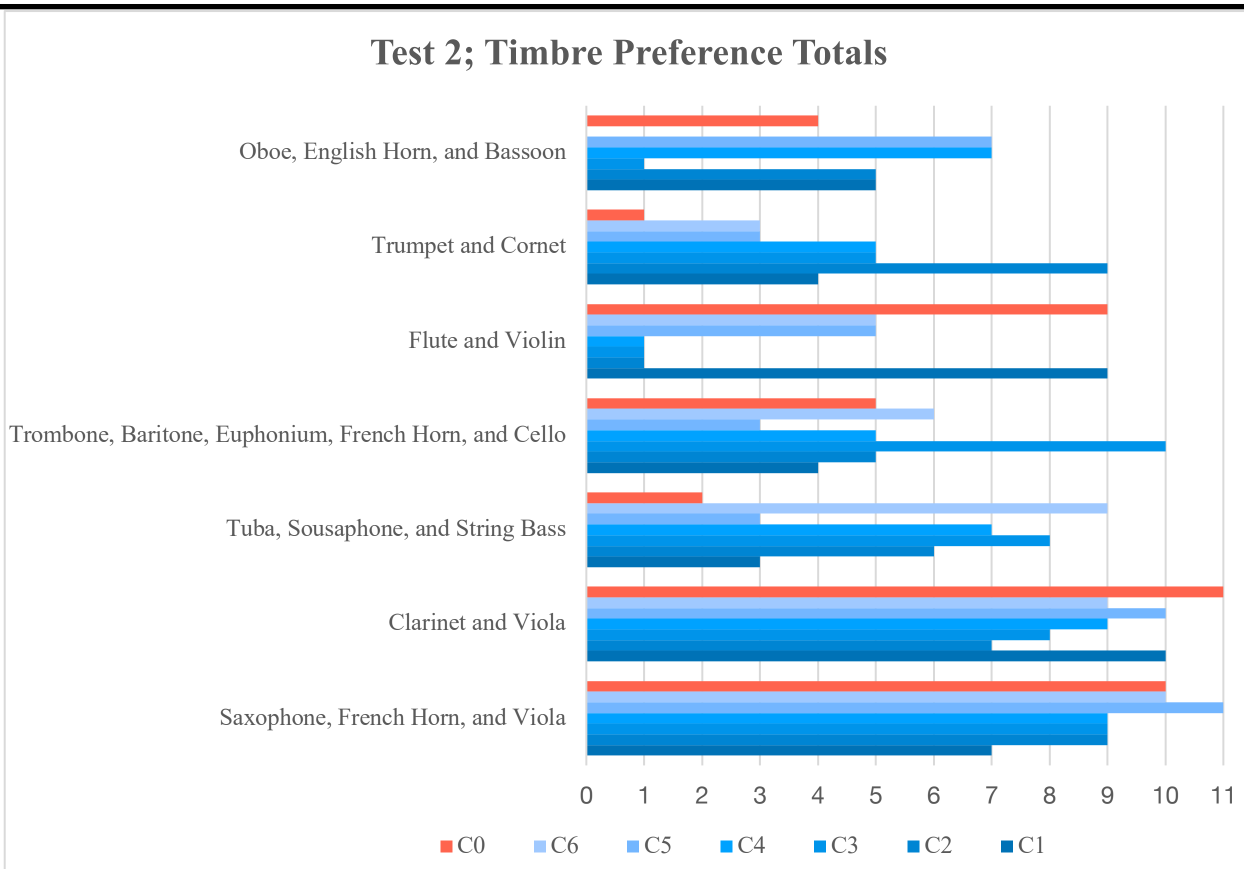


Figure 11. Results for the Timbre Preference test (Test 2) for all participants' rankings. Instrument timbre groupings are marked on the Y axis, and grouped from the cumulative most liked group, to the least (bottom to top). CI study participant marked as "C0".

Results shown on Figure 11 (above) can be interpreted in three main sections, detailing which timbres were the most preferred, which were rated average overall in subjective preference, and which were least preferred overall, using average ratings. A score of 0 represents an instrument group never being chosen as "preferred", and a score of 11 represents an instrument group chosen every time over another (see Table 3, below).

Timbre Groupings	*Octave range*	*Average rating RH and CI (0-11)*	*Total Score*
Most preferred timbres			
Saxophone, French Horn, and Viola	Mid-range	9.29	65
Clarinet and Viola	Mid-range	9.14	64
Average in preference			
Tuba, Sousaphone, and String Bass	Low-range	5.43	38
Trombone, Baritone, Euphonium, French Horn, Cello	Low-range	5.43	38
Least preferred timbres			
Flute and Violin	High-range	4.43	31
Trumpet and Cornet	High-range	4.29	30
Oboe, English Horn, and Bassoon	Mid-range	4.14	29

Table 3. Timbre Preference (Test 2) results. Categories of preferred, average and least preferred timbres established by closeness in standard deviation of answers. Total score is the sum of all answers, out of a maximum of 77 if all participants were to choose a timbre as their preference.

The two most preferred timbre categories were identified as both mid-range octave groupings; the clarinet / viola, and saxophone / French horn / viola groupings. Also notably, the grouping mimicking the violin / flute was among the least preferred timbres on average for RH, while also being the timbre grouping with the most "least preferred" ratings of 1 attributed to it. Despite this, the CI study participant rated this grouping highly with a score of 9. Based on these aggregates, we can conclude that results are very individualistic, and although trends can be seen, personal preferences of participants might not necessarily fall within the most popular timbres.

Similarities in timbre preference are determined by closeness between the study participant's preference, and the RH comparison group's averages. Any of the study participant's preference ratings that fall within one standard deviation of RH ratings will be considered as similar. Out of 7 possible timbre groupings, 3 (or 43%) stood out with similar results between the study participant and the comparison group; the oboe / English horn / bassoon grouping, the trombone / baritone / euphonium / French horn / cello grouping, and the saxophone / French horn / viola grouping. On average, the saxophone / French horn / viola grouping the most agreed upon preferred timbre grouping between all participants, as also seen above.

The study participant's personal timbre preferences compared to the RH group's average are included in Table 4, as well as Figure 12 (see below).

Timbre groupings	*CI participant's ratings*	*RH average*
Clarinet and Viola	11	8.83
Saxophone, French Horn, and Viola	10	9.17
Flute and Violin	9	3.67
Trombone, Baritone, Euphonium, French Horn, Cello	5	5.50
Oboe, English Horn, and Bassoon	4	4.17
Tuba, Sousaphone, and String Bass	2	6.00
Trumpet and Cornet	1	4.83

Table 4. Timbre Preference (Test 2) CI and RH results. Instrument timbres are ranked out of a possible score of 11, and placed in order of preference, as compared to the CI study participant's preferences.

From highest rated groping to lowest, there is a clear correlation on 6 out of 7 of the timbres in terms of octave range; most preferred timbres were higher and mid-ranged octave instruments, whereas lesser rated timbres were associated with low-octave instruments. This correlation is also seen with the RH study group, as previously demonstrated in Table 3 (see above). The study participant's lowest rated grouping does not follow this trend, being the high-octave trumpet / cornet grouping, with a score of 1, which also correlates among the RH comparison group's least preferred timbre groupings. The study participant's most preferred timbre grouping is the same as the RH group's – the mid-octave ranged saxophone / French horn / viola grouping.

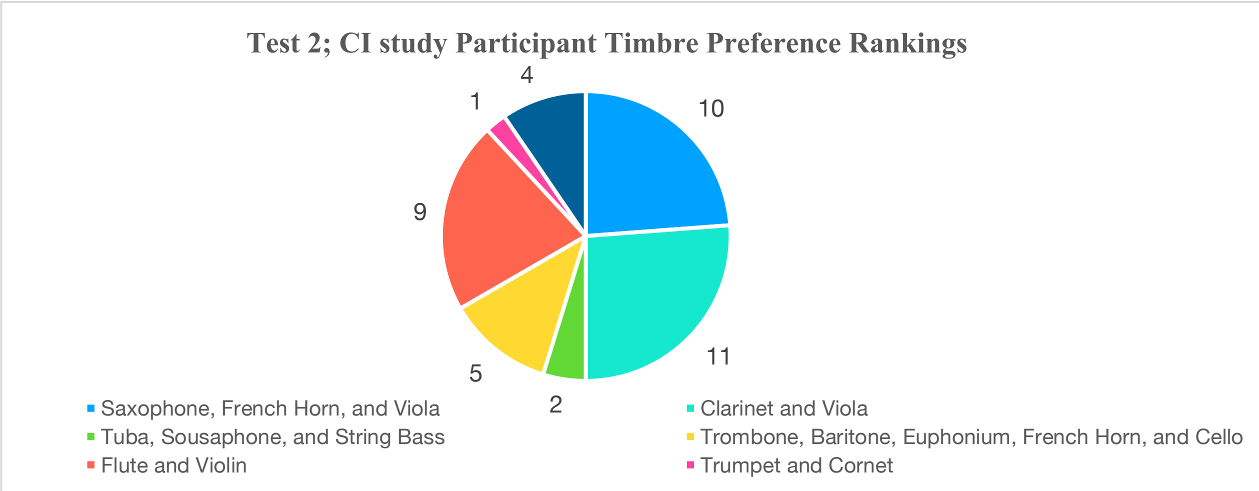


Figure 12. Results of the Timbre Preference test (Test 2) for the CI study participant's individual rankings of timbre groups. Larger sections represent preferred groups.

4.3 Test 3 Results - Tonal and rhythmic audiation

Test scores were analyzed individually for the rhythmic and pitch portions of the experiment. In terms of tonal pitch discrimination, the study participant fell below average and not falling with standard error bounds when compared to RH participants, with 20/40 correct answers (the RH average being 29.33/40). The study participant received the lowest score in tonal pitch discrimination; however, it is noted that he was not the only participant to receive a score outside of the RH standard error bounds, with two RH participants scoring much higher and much lower than the average score, respectively (see Figure 13 and Table 5, below). For rhythmic discrimination, the study participant scored better than tonal perception, with 24/40 correct answers (the RH average being higher at 30.33/40). Contrarily to tonal pitch perception however, the study participant's score was not the lowest of all participants, and his answers fell with the standard error of the RH group's answers, meaning his rhythmic discrimination score is similar to that of RH counterparts.

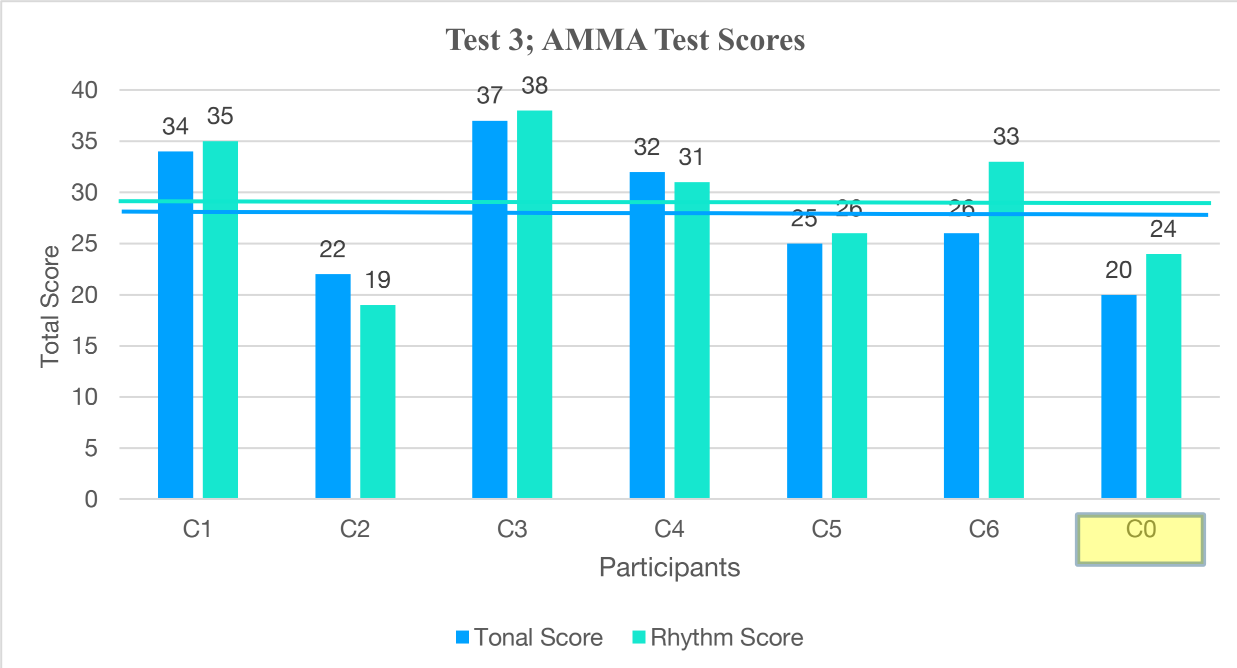


Figure 13. Results for the Advanced Measures of Music Audiation Test (Test 3), including tonal pitch perception scores in blue, and rhythmic perception scores in light blue. Group averages are shown as horizontal thresholds on the graph. Results are shown for all participants, with the CI study participant on the right, marked as "C0".

Participant	*Tonal Score*	*Rhythm Score*	*Tonal PR*	*Rhythm PR*	*Composite PR*
C1	34	35	87	83	80
C2	22	19	17	1	4
C3	37	38	96	93	94
C4	32	31	76	58	62
C5	25	26	32	22	26
C6	26	33	38	72	50
C0	20	24	8	11	9
RH Average	29.33333333	30.33333333	57.6666667	54.8333333	52.6666667
RH st. dev	5.853773712	6.860515044	32.7576963	36.1409279	33.5539367

Table 5. Advanced Measures of Music Audiation (Test 3) scores, split into tonal pitch perception scores and percentile ranks, and rhythmic perception scores and percentile ranks. Scores are out of a possible 40 points, and PR out of a possible 100, as compared to datapoints of undergraduate student responses through the United States (Gordon, 1991). CI study participant marked as "C0".

It is also noted that once more, two RH participants fell outside of one standard deviation from the comparison group's average, one with a much higher score and one with a much lower score respectively (see Figure 14, below). In addition, a majority of participants (5 out of 7, including the CI study participant) demonstrated better rhythmic discrimination scores when compared to tonal pitch discrimination scores.

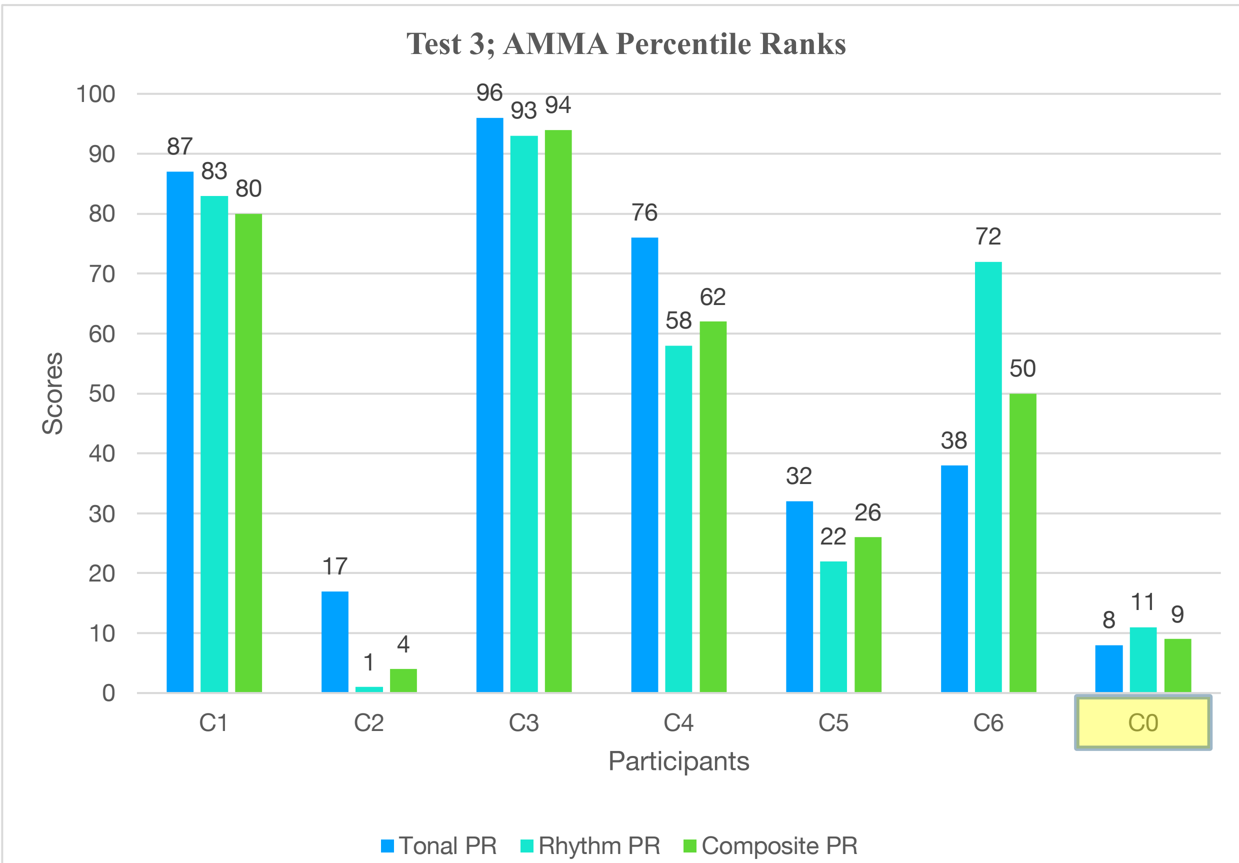


Figure 14. Percentile Ranks (PR) for the Advanced Measures of Music Audiation Test (Test 3), including tonal pitch perception PR in blue, rhythmic perception PR in light blue, and composite total PR in grey. Results are shown for all participants, with the CI study participant on the right, marked as "C0". Percentile ranks determined by datapoints of undergraduate student responses through the United States (Gordon, 1991).

Percentile ranks are attributed to individual and composite answer scores, based on Gordon's previous studies on Advanced Methods in Music Audiation, and compared to test scores of RH music and non-music students in secondary, and post-secondary schools in the United States (ages 12 and above) (Gordon, 1991). The study participant demonstrated percentile ranks of 8 for tonal discrimination, and 11 for rhythmic discrimination, falling under Gordon's average for RH undergraduate music students (between the 20th-89th percentile ranks, see Figure 15, below). This represents the lowest tonal pitch discrimination percentile rank between all RH participants tested in our study, and the second-lowest rhythmic discrimination percentile rank. Of all six RH participants, only one exceeded percentile ranks of 90, falling under Gordon's definition of a music student expected to excel in their music studies (Gordon, 1991). One RH participant fell under Gordon's average for RH undergraduate music students (under the 20th percentile rank), with answer scores very similar to the study participant.

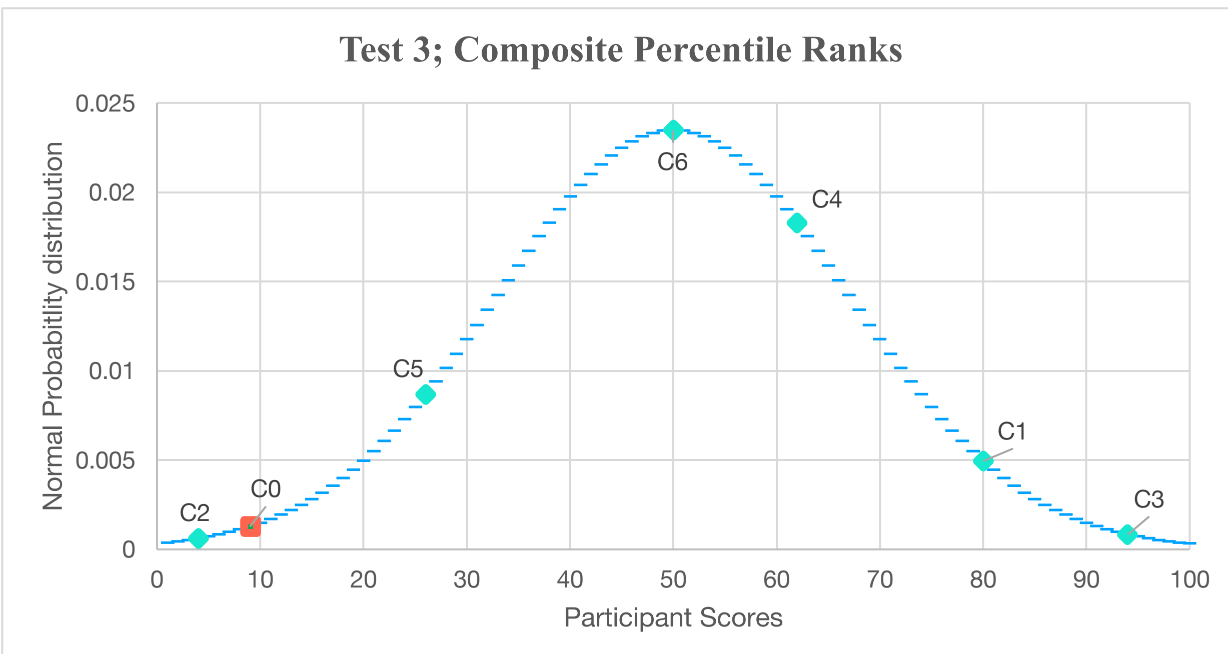


Figure 15. Composite Percentile Ranks (PR) for the Advanced Measures of Music Audiation Test (Test 3). Scores include a composite between tonal pitch perception and rhythmic perception. PRs are placed on a normal distribution of results, as established by Gordon's threshold of representation for most likely PRs to excel in musical studies (between 20th-89th percentile) (Gordon, 1991). CI study participant marked as "C0".

4.4 Discussion

This study investigates a violinist CI user's pitch perception, timbre preference and melodic discrimination skill (regarding pitch and rhythm) in comparison to RH violinist peers, as well as known shortcomings within the CI technology's translation of musical qualities. The research hypothesis states that due to the study participant's high-achieving education and success in playing a pitch-heavy instrument, that he may exhibit higher than previously recorded pitch perception skills compared to other CI users, and therefore similar pitch perception skills when compared to violin-playing RH peers. In addition, the literature suggests that the study participant would still demonstrate comparable timbre preference and rhythmic perception skills as RH participants.

Test 1 and Test 3 both had components focussing on tonal pitch perception and discrimination, and it was expected to see overlap between results of the tests. In literature, pitch and tonal processing is distinguished as a primary weakness for a CIs when compared to the RH ear (Innes-Brown et al., 2013; Petersen et al., 2015; Stabej et al., 2012). When tasked with matching pitches as closely as possible, only 16% of adult non-musically trained CI users could match a pitch successfully at a 1-2 semitone difference (Wang et al., 2011). In Test 1, our CI study participant succeeded in matching to a 1 semitone range in 60% of subtests, while even staying within the 1 semitone range on average through all subtests, which is remarkably higher in comparison. Children with CIs have also been noted to demonstrate correct melodic pitch discrimination for between 50-60% success rates, at a 5-semitone interval closeness of pitch (Chen et al., 2010). Our case study reached a similar level of pitch closeness, but at a much more precise interval range of 1 semitone, also suggesting better results in comparison to previously studied CI users in terms of pitch perception. It is also notable that the study participant's pitch perception scores were 60% in Test 1 and 50% in Test 3, acting as a confirmation of similar results for both tests, and validation of the study participant's overall pitch perception ability.

In terms of capering RH tonal pitch perception to that of CI users, as a primary weakness, it is expected that the study participant would have lower pitch perception scores than the RH comparison group. Innes-Brown and colleagues (2013) identified CI user results as being anywhere between 10-21% lower than RH counterparts for tonal pitch perception using the Intermediate Measures of Music Audiation test by Gordon (1991), similar but much less demanding than our Test 3. Given that the AMMA test is known as a more rigorous and complete testing of audiation compared to the IMMA (Gordon, 1991), it is not unusual that the study participant would demonstrate a tonal pitch perception success rate of roughly 31% less than the RH comparison group. As noted above in Test 1, the study participant was able to not only keep results similar to the RH comparison group on 40% of subtests, but also demonstrated better precision in terms of answers than the RH group on 90% of subtests – demonstrating that although his pitch perception on average was lesser than that of RH peers, his pitch precision was much more successful. Overall, results resonate with the literature, in terms that our study participant's pitch perception was lower than that of RH counterparts but is also higher than that of previously tested CI users. It is believed that this is the case due to the study participant's incessant passion for the violin, a pitch-heavy instrument, and how despite being told by music teachers and audiologists alike that it would be a more difficult instrument for him to learn, his stubbornness paid off in terms of his music learning (Saunders, 2021) – developing his own methods and accommodations for understanding pitch through the CI, and demonstrating pitch perception skills beyond previously seen for CI users.

In addition, although these results were collected over averages, there exist many cases within subtests in Test 1 and Test 3 where the study participant performed much better than his own average pitch perception, and better than that of some RH peers, notably for pitch matching within frequencies very close to the range of the human voice (329.6Hz, 523.3 Hz and 622.3 Hz). As these ranges of frequencies are the most effectively captured through the CI filtering, it is believed that the study participant would also be most accustomed to these frequencies, and therefore more successful in identifying them, when compared to lower frequencies < 300 Hz that would be difficult to process through the CI (Limb & Roy, 2014).

Timbre preference was evaluated only through Test 2, through the subjective ranking of synthesized tone colours in order to pinpoint which instrument timbre and octave range is most enjoyable to the CI user, as compared to RH participants. It is believed that although all participants would have their own respective personal preferences, that timbres associated with strings would be ranked highly overall, being every participant's main playing instrument. Timbre has previously been seen as a musical quality that shouldn't be processed too differently through a CI when compared with the RH ear, meaning we can expect general timbre preferences to be similar between the study participant and the comparison group (Kim et al., 2015; Vongpaisal & Managhan, 2014; Innes-Brown et al., 2013.) Through the CI's particular tone and pitch filtering, it was also expected that the study participant would dislike brass and woodwind timbres and low octave ranged timbres (Limb & Roy, 2014; Moran et al., 2016; Kim et al., 2015).

The two most preferred timbre groupings are the same between the CI study participant and RH comparison group; the mid-octave range clarinet / viola group, and the mid-octave range saxophone / French horn / viola group. These two groupings are distinctly at much higher ratings than other groups, demonstrating a clear preference for all participants alike. These groupings also represent mid-octave ranges, well within the most effective processing range of the CI, as expected. The main distinction between the study participant and comparison group in terms of favourite timbre groupings is that the CI participant ranked a third category very highly (rank of 9 or above): the high octave range of the flute / violin grouping. Although the comparison group did not agree with this high ranking, it is understood that the CI participant has always demonstrated a very prominent and passionate preference for the violin's timbre, throughout his childhood, education and despite recommendations against the instrument because of his CI (Saunders, 2021), and this preference is demonstrated here through results. As expected as well, the case study's least preferred timbres both represented strong brass at the forefront, the tuba / sousaphone / string bass group, and the trumpet / cornet group.

Comparing RH timbre preferences to that of the study participant, it was established that results were similar for 43% of answers. When comparing any given participant to the rest of their counterparts, any RH participant is seen to have similar results to the group only for 29% of answers, on account of a large group standard deviation (2.345) and variance (5.719). This means that the CI participant demonstrated among the most similar of the average in timbre preference overall, compared to all RH participants. This is pertinent, as it was not expected for timbre to be a difficult musical quality for the CI to process and demonstrated that the study participant's timbre preference is well within the average found timbre preference of an RH comparison group.

Finally, rhythmic perception was tested within the AMMA Test 3, alongside results above on tonal pitch perception. Similarly to timbre perception, rhythmic perception has been pinpointed as another musical quality that can be processed well through the CI, and it was expected for the case study to demonstrate similar rhythmic perception skills as RH counterparts (Kim et al., 2015; Vongpaisal & Managhan, 2014; Innes-Brown et al., 2013). It is understood that rhythmic cues are a primary factor in understanding timbre, melody and instrumentation for a listener, and CI users have often identified strong timbral cues not only as being essential to music enjoyment and identification, but also as an essential quality for a CI to process (Kim et al., 2015).

Test 3 rhythmic perception results were more successful across the board both for the study participant and for 2/3 of RH participants. Additionally, the study participant's rhythmic perception score (24/40) fell within error bounds of one standard deviation of the RH average score (30.33/40, st. dev: 6.86). This not only demonstrates the similarity between the rhythmic perception of CI and RH participants but also how it is more successful than tonal pitch perception seen above for Test 3 - whereas tonal pitch perception is identified as a weakness for the study participant, rhythmic perception is not. In terms of percentile rank, although the study participant's rhythmic ranking falls under the 20th percentile (pinpointed by Gordon (1991) as being a threshold for most average RH music students in the United States), it still falls within the range of the RH study group for this experiment, as it is higher than the lowest percentile rank of the comparison group. This demonstrates how the study participant's rhythmic perception is comparable to that of RH peers, as expected from previous literature.

5. Conclusion

The study of musicians who use cochlear implants is not novel, but the kind of instruments being studied has often been more percussive, with less dependency on pitch precision. The success seen by our CI using participant Leo at the violin is mostly unheard of, and counters most literature found regarding difficulties in pitch perception most CI users face. A related study to this one, written by Saunders (2021), found that the participant's background in early music learning with his family, along technique accommodations developed over the years have encouraged Leo not only to play the violin, but excel at it despite his hearing ability.

Because of Leo's astonishing success with the violin, it was determined that his pitch perception skills would seem beyond what has been previously studied and understood for CI users and might also apply to other musical qualities such as timbre preference and rhythmic perception. Through case-control comparison with RH violin-playing peers, it became possible to investigate these musical qualities as compared to previous known CI users, and RH participants alike. In these tests, Leo demonstrated a better pitch perception than expected by CI literature, albeit not as successful as the RH comparison group, and a highly comparable timbre preference and rhythmic perception ability to RH peers. It is expected that Leo's background in music education from an early age and his incessant passion for the violin despite known limitations (Saunders, 2021) were crucial factors in his phenomenal perception of musical qualities and might shed light on better understanding the limitations (and lack thereof) of CI technology's processing of musical qualities.

Limitations in this study include the low number of candidates, due to the multiple obstacles in recruitment associated with the COVID-19 pandemic. It is also noted that although the tests were designed to compare the CI's capabilities in pitch, timbre and rhythm perception, the tests incorporated synthesized and recorded sounds. It is understood that the use of physical instruments might be more accommodating to the way the CI participant intakes musical information through his CI, through vibroacoustical feedback and through physical cues (Saunders, 2021), and such accommodations could provide an even higher success in musical perception for the case study participant as well as the RH comparison group. Although this study's scope is limited, comprising of a very small sample comparison group and a singular study participant, the emphasis of this inquiry lies in the unprecedented singularity of Leo's (and his guardians' and teachers') devotion and prowess. Examples like Leo's can provide audiologists, music teachers and musicians alike with the knowledge that previously known limitations of CI technology might not be so limiting after all.

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Appendix 1 – Supplementary Material

uOttawa
École de musique
School of Music

Violinists Wanted

PIANO Lab
Laboratoire de recherche en Pédagogie du piano
Piano Pedagogy Research Laboratory

Researchers at the uOttawa Piano Pedagogy Research Laboratory are conducting a violinist case study, and are in need of a comparison group of violinists.

What participants will be asked to do:
- Fill out a questionnaire with general demographic questions and music experience questions (15 minutes)
- Complete a battery of music perception tests (approximately 1 hour) as follows:
  - Melodic discrimination tests
  - Pitch matching tests
  - Pitch difference tests

To be eligible, participants must:
- Be of age 18 to 24
- Be studying violin performance at a university level
- Not have any hearing impairment

When:
- Sessions will be scheduled at your convenience, starting in June 2022

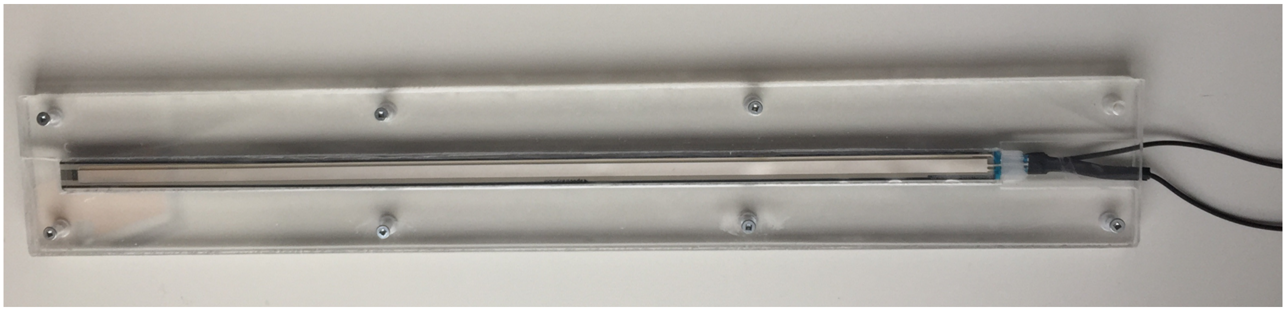
Location
- uOttawa Piano Pedagogy Research Laboratory, Perez Hall, 50 University St, Room 204

Safety precautions
- All surfaces that participants will be in contact with will be disinfected prior to the session. - Participants and test administrators will maintain a minimum of 2m distance during the entire session.
- The only persons present during the session will be the participant and one or two test administrators. Masks must be worn at all times.

This project has been reviewed and has received ethics clearance by the University of Ottawa Social Sciences and Humanities Research Ethics Board. If you have any questions regarding the ethical conduct of this study you may contact the Protocol Officer for Ethics in Research, University of Ottawa, Tabaret Hall, 550 Cumberland St, Room 154, Ottawa, ON K1N 6N5. Tel: 613-562-5387, email: [redacted]

Please contact [redacted] for more information and to participate.

Supplementary Material 1. Recruitment poster used at the University of Ottawa for the RH comparison group, made at the University of Ottawa Piano Pedagogy Research Laboratory by myself, with the help of the laboratory coordinator, Mikael Swirp.



Supplementary Material 2. Pitch matching tactile slider, used for Test 1. The slider is a pressure sensor strip, mounted on a hard surface. The slider is currently used at the University of Ottawa Piano Pedagogy Research Laboratory, and was developed in Montreal, Québec in partnership with Infusions Systems and the Université de Montréal (Hutchins & Peretz, 2012).

Pitch	*Frequency (Hz)*	*Hertz diff to next pitch*	*JHD (Hz)*	*JHD (cents)*
$A^{\#}_3/B^b_3$	233.08	148.02	3	12
B_3	246.94	139.71	3	12
C_4	261.63	14.69	3	12
$C^{\#}_4/D^b_4$	277.18	15.55	3	12
D_4	293.66	16.48	3	12
$D^{\#}_4/E^b_4$	311.13	17.47	3	12
E_4	329.63	18.5	3	12
F_4	349.23	19.6	3	12
$F^{\#}_4/G^b_4$	369.99	20.76	3	12
G_4	392	22.01	3	12
$G^{\#}_4/A^b_4$	415.3	23.3	3	12
A_4	440	24.7	3	12
$A^{\#}_4/B^b_4$	466.16	26.16	3	12
B_4	493.88	27.72	3	12
C_5	523.25	29.37	3.14	12.558
$C^{\#}_5/D^b_5$	554.37	31.12	3.33	13.30488
D_5	587.33	32.96	3.52	14.09592
$D^{\#}_5/E^b_5$	622.25	34.92	3.73	14.934
E_5	659.25	37	3.96	15.822
F_5	698.46	39.21	4.19	16.76304
$F^{\#}_5/G^b_5$	739.99	41.53	4.44	17.75976
G_5	783.99	44	4.7	18.81576

Table 1. Musical Pitches and equivalent studied frequencies (Suits, 1998). Including the just-noticeable difference (JHD) between pitches in frequency (Hz) and cents.