Critical Review:
Which CI Strategy is the Most Successful for Music Appreciation

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This critical review examines the effects of different processing strategies on music perception and appreciation in adult CI users. Studies included investigate music perception in adult CI users, other factors affecting music appreciation scores, and comparison of different types of CI strategies in current use. Study designs include: single group clinical trials, randomized controlled trials, and quasi- experimental designs with case control. Overall, results indicate that CI users do not perform as well as normal controls regardless of CI strategy for music perception. However, new and improved CI strategies that include higher stimulus rates and increased fine structure information have been documented to enhance perception of music. There is no clear consensus that one specific type of CI processing strategy is superior for music listening. Further explanations for this are explored and clinical implications are included.

Introduction

Cochlear implants (CI) are assistive hearing devices designed for those with severe to profound sensorineural hearing loss. Modern CI systems provide good speech understanding in favorable listening situations. There has been a growing request by patients to be able to appreciate music. Beyond beneficial effects on cognitive and emotional functions, improved music perception is highly desirable and could improve quality of life (Bendixen, Debener, Dillier, Eichele, Jancke, Kegel, Lai, Mever, Sandmann, 2010). There are many ways of defining musical sounds, making it difficult to define the construct of music perception. What categorizes music differs among cultures societies, and numerous subjective factors influence music appreciation (Drennan, Kang, Longnion, Nimmons, Rubinstein, Ruffin, Worman, Yueh, 2008). Some of those subjective factors may include one's personal preferences for musical genre, listening environment, and listener's mood; all of which can affect music appraisal. Studies conducted in this area analyze music perception ability by focusing on the characteristics of acoustic signals that correspond to structural features of music including rhythm, pitch, melody, and timbre (Drennan et al, 2008).

Previous studies have shown that CI users' perceptual accuracy is similar to normal hearing adults for simple rhythms (Drennan et al., 2008). Since rhythm perception is relatively good in CI users, the features of music perception that will be investigated include pitch, timbre and melody recognition. Because these features are being investigated in this review, it would be helpful to define each of these and describe their role in the ability to perceive musical sounds.

Pitch is the perceptual correlate of frequency; a good perception of complex tone pitch relies on repetition rate because there is no single site of stimulation. Perception of complex-tone pitch is primarily dependent on fine structure temporal encoding. Different ways of testing pitch include discrimination and rank tasks (D'haenens, Dhooge, Keppler, Maes, Philips, Vel, Vinck, 2011). Timbre differentiates between sounds of the same pitch, loudness, and duration, such as when distinguishing the same musical note played on different instruments. Timbre based tests include musical instrument identification (D'haenens et al., 2011). Melody recognition based tests can include familiar melody contour tests (Drennan et al., 2008).

The aim to improve music perceptual ability in CI users has lead to the development of different cochlear implant processing strategies. A signal coding strategy for cochlear implants involves the algorithm used to transform important features of incoming acoustical signal into an electrical signal. One main processing strategy is Continuous Interleaved Sampling (CIS) and its many variations. In the CIS strategy, pulse trains from the electrical signal are generated for different corresponding electrodes through non-simultaneous stimulation. This non-simultaneous repetition rate is similar to the firing of the auditory neural fibers with different refractory and firing periods which reduces electrode interaction (Dorman & Wilson, 2008).

These strategies transmit repetition rate information of the envelope. However, these strategies also have high frequency cut-off limit for the envelope modulation (from 300Hz to 1000Hz) depending on the specific strategy (Dorman & Wilson, 2008). Also, the effective number of channels along the length of electrode array is limited from 4 to 8 sites even for arrays with more electrodes due to inter-cochlear interference. Therefore, much of temporal fine structure (TFS) information is missing and fundamental low frequency cues are not transmitted very well. Currently, CI strategies have been developed to increase the spectral resolution required for music perception to enhance music appreciation. One such strategy is referred to as the Fine Structure Processing Strategy (FSP) that encodes the temporal aspects of the waveform at the low frequency regions of the array.

Objectives

The primary objective of this review is to determine which CI processing strategies result in enhanced music appreciation by looking at perceptual tests with CI users. The CI interventions will be critically evaluated in terms of music perception scoring. Clinical recommendations about specific intervention for the adult CI population will be discussed.

Methods

Search Strategy
Computerized databases MELINE, SCORPUS, and PubMed were searched using the following strategy (cochlear implant processing strategies*) AND (music perception) OR (music appreciation). The search was limited to articles written in English.

Selection Criteria
Studies selected for inclusion in this critical review were required to investigate performance on music perception tasks by adult CI users. The reviewed studies also examined the effects of the type of cochlear implant strategy in regards to speech perception and other factors. However this review only investigates the effects of cochlear implant processing strategies on music perception for CI users. Participants in the studies were adults with post-lingual deafness.

Data Collection
A review of the research yielded four studies. Two out of the four studies consisted of a single group study design (*study 1*, *study 4*).The other two studies consisted of a randomized block design (*study 2)* and a non-randomized case-control design (*study 3).* Three of the four studies provided grade III level of evidence and one out of the four studies provided a grade II b level of evidence. The studies were broken down into categories regarding assessment of music perception and appreciation. *Study 1* and *study 2* in this paper addresses adult CI users' performance in music perception based tasks. *Study 3* addresses some of the issues involved in subjective-based measures of music appreciation. *Study 4* involves a direct comparison between different CI strategies in terms of music perception ability.

Results

Assessment of Music Perception and Appreciation in Adult CI Users

Study 1: Evaluating Music Perception

Drennan et al. (2008) made use of a short computerized test, the Washington Clinical Assessment of Music Perception (CAMP), to assess pitch discrimination, melody identification, and timbre identification. The participants consisted of a prospective convenience sample of eight adult experienced CI users. The test involved a counterbalanced pitch ranking procedure (with practice sessions), randomized and familiarized melody recognition using live recordings (with practice sessions). The study was a single group series design. Statistical analyses used mean scores of percent correct and standard deviation values.

Results from this study included frequency discrimination performance that ranged from a minimum difference limen (DL) of 1 semitone to maximum of 11.1 semitones across frequencies. Synthetic Melody percent correct scores ranged from 6% to 81% correct, with a mean across subjects of 23% and large variability. Timbre Scores ranged from 21% to 54% correct for CI listeners, with a group mean of 49% and a spread of 11%. CI listeners were more likely to select brass or string than other woodwinds. This has been reported in previous tests, supporting the external reliability of this measure. Extremes of performance suggest that CI users with frequency discrimination thresholds greater than 1 semitone at any base frequency will exhibit poor melody recognition. For example, the authors found that one listener (L5) who had the high pitch thresholds and mean scores for frequencies included in melodies also had the lowest melody recognition scores (11%) and lowest timbre recognition score of 21%. Overall, listeners scored higher on the timbre test than the melody test.

These results are in agreement with previous studies of music perception in adult CI users. However, there is currently no gold standard music perception test to directly compare results across studies on CI performance. Therefore, one must be conservative in drawing conclusions from experimental findings. The CAMP demonstrated a broad range of perceptual accuracy in CI listeners for all three subtests. However, in order to increase the external reliability of this test, multiple administrations of the CAMP to sample groups within the target population are needed. Caution should be used in generalizing melody recognition results because they were instrumental recordings while real melodies have transient note durations or lyrics. Another shortcoming is that CI users were not equipped with newer CI strategies except for one subject (*CIS, ACE, and HiRes/HiRes-P 120 for subject L7)*.

Study 2: Specific Cues involved in Music Perception

Kong, Singh, and Zeng, (2009) evaluated the contributions of spectral and temporal cues to melody recognition in CI users. They did this with recognition of melodies in three frequency ranges (low = 104-262Hz, middle = 207-523Hz, high = 414- 1046Hz ranges). Authors also compared recognition between pure and complex harmonic tones over those frequency ranges. This randomized block design study included two experiments using a prospective sample group of experienced adult CI users, with eleven CI users in the first experiment for recognition of simple melodies. Four of those eleven subjects were included in another experiment to compare performance of simple versus complex melody recognition.

In the first experiment, correct percentage scores for melody recognition in different frequency ranges revealed an increase in performance as melody frequency range increased. Repeated measures ANOVA post hoc two-tailed comparisons revealed that frequency range was a significant factor ($p < 0.001$) that influences cochlear implant melody recognition. In the low frequency ranges there were poorer scores (15.7%) compared to mid frequency range scores (42.3%) and high frequency range scores (64.9%) on average. In the second experiment, pure tone melodies produced significantly better performance ($p < 0.05$) than complex tone melodies. Frequency range was also significant factor to determine amount of improvement (20.4 = low frequency, 24.5 = mid frequency, 8.0 = high frequency percentage points in improvement).

These results are consistent with the theory that better representation of both temporal and place cues for pitch produces better melody recognition. The results of this study also indicate that cochlear implants cannot process complex tones effectively particularly in the low and mid-range frequencies. One issue related in making generalizations from this study is that the authors do not explain why some subjects in the first experiment were excluded in the second experiment. There was no randomization of participants because they came from the available population pool. Also, all experimental results from this study are from CI users that have the CIS strategy only (*CII-CIS, n-of-m SPEAK and ACE*).

Individual Variability found in Music Appreciation

Study 3: Neurological factors

The experimental designs discussed have been acknowledged to be artificial compared to the challenges faced by CI recipients for music listening. Subjective appreciation of music is not well reflected within laboratory conditions. Many other variables are to be accounted for, such as personal, situational, cultural, and emotional factors. Previous research tends to focus on music perception rather than appreciation in adult CI users, or to focus on enjoyment via self-reported questionnaires. Music appreciation studies have shown inter-subject variability in appreciation ratings (D'haenens et al., 2011). Accounting for factors contributing to variability has important implications for deciding between different CI strategies.

For this reason, Bendixen et al (2010) investigated neural and behavioral correlates of musical sound perception in adult CI users and normal hearing (NH) individuals. Specifically, experimenters measured music perception through behavioral discrimination tasks and counterbalanced mismatch negatively (MMN) recordings in CI users. In the NH control group, experimenters used counterbalanced MMN recordings as well as discrimination profiles of musical sounds through vocoded and original recordings. The Quasi-experimental design was a non-randomized case-control clinical trial study for a prospective sample consisting of twelve CI users with matching controls.

Results of this study were collected using mixed ANOVA analyses for behavioral performance in music discrimination. A linear regression analysis was used to determine an association between behavioral performance and the MMN amplitudes in each group. Distinct MMN amplitude responses could be identified for frequency deviants (CI users = 186 msec, NH listeners = 178 msecs original, $p < 0.001$) and between the CI and NH ($p < 0.05$) groups. Authors concluded that the behavioral and electrophysiological results matched and that there was worse discrimination in CI users for changes in frequency, intensity and duration of musical sounds. This is consistent with previous findings in which CI users have difficulty in melody, timbre, and pitch discrimination.

The multi-feature MMN paradigm can be used as an objective clinical tool in order to evaluate discrimination abilities of CI users for music perception. However, further replications are needed to increase the reliability and validity of this measure. The MMN index of auditory discrimination accuracy between group analyses of CI versus NH subjects and reducing artifact in the measure makes it difficult to compare CI users to NH listeners. Also, one cannot generalize conclusions from this study to other devices because all subjects had the Freedom processor CI systems, belonging to the Cochlear Ltd Company using the ACE strategy (*n-of-m strategy; a variation of CIS*).

Another factor that makes it difficult to generalize the conclusions from this study is that there was a variance of age (38-70 years) that can affect the differences between both groups. Finally, there was only one type of instrument used for the musical tasks in this study, the synthesized clarinet tone. Therefore, it would be difficult to generalize results to live music listening. Across studies, there appears to be a trade-off between generalization of results and better control of acoustic properties and this makes it problematic to compare performance measures between CI and NH subjects. Also, other cochlear implant strategies or models may yield different results when comparing CI user to NH groups for music perception performance.

A Comparison of Cochlear Implant Processing Strategies for Music Listening

Study 4: Comparison of CI strategies

The CIS strategy and variations of CIS (such as the n-of-m) are able to process sound for CI users. The n-of-m strategy identifies signals with the highest amplitudes (n) from the electrode array (m) for perception. A new and major variation of CIS is the Fine Structure Processing (FSP) strategy. Fine frequency information is represented in the low frequencies by capturing the temporal aspects of the waveform (not the case for other CIS strategies) using zero crossings that focus on parts of the waveform in pulse pockets. For high frequencies, FSP performs similar to CIS. Results from previous studies have indicated improved scores for music appreciation after conversion from CIS to FSP (Rosslau, Saafeld, Spreckelmeyer, Westhofen, 2011).

One study by Magnusson (2010) aimed to evaluate the FSP strategy in comparison with another new variation of the CIS strategy; High definition CIS (HDCIS). The hypothesis assumes that both strategies should better provide fine spectral information, improve pitch perception and, thereby, increase music appreciation. This quantitative experimental design involved a sample of twenty experienced adult CI users. The subjects underwent double blinded paired-comparisons between the FSP and HDCIS for music quality. There were immediate and long term follow-up appointments (six months and two years) in a randomized order. Subjects used the FSP at first follow-up and FSP or HDCIS at the second.

Results of the study included measures for differences between sessions using repeated measures ANOVA and a Bonferroni adjusted post-hoc test. Significant differences between strategies were analyzed via Wilcoxon signed ranks test. The repeated measures ANOVA revealed no significant within-subject difference ($p = 0.08$) between the three sessions. Paired comparisons results showed no significant differences (Wilcoxin: $p = 0.13$) between strategies.

The results indicate that the FSP strategy may not be superior to other new CIS strategies. However, this non-significance can be due to the higher stimulation rate of HDCIS (3000pps) which carries more fine structure information with faster stochastic firing rate. The experimental design itself had many flaws. For example, the alternative switching between FSP and HDCIS was not counterbalanced. Subjects' prior CI experience may have influenced preference for a strategy that was similar to their prior CIS device, and this happened to be the HDCIS strategy. Finally, previous studies demonstrated that, although CIS strategies yielded higher scores for melody recognition, FSP strategies yielded higher scores for the rhythm test and the number of instruments tests. Also, subjects were asked to evaluate the pleasantness of the melody and this may measure enjoyment, but not necessarily accuracy of music perception; a factor that is also involved in music appreciation. Therefore, the validity of this subjective measure should be questioned.

Authors did mentioned another current strategy that can be considered as a variation of CIS; the HiRes Fidelity 120. In this strategy, virtual channels are employed to increase the number of distinct electrode sites beyond the number of physical electrodes. Virtual channels are created when adjacent electrodes are stimulated simultaneously to shift perceived pitch in any direction with respect to pitch perception of the stimulation for either electrode alone. The authors did not include the newer type of strategy in the study for comparison.

Discussion of Results and Alternative Interventions

In the other three studies investigated a comparison was attempted in order to investigate which CI strategy faired the best out of the three study populations used. *Study 1* had a variety of CI strategies included in their CI populations and demonstrated that those with poor frequency discrimination would not be able to perform well in music related tasks such as melody and timbre recognition. However, only one subject was implanted with a newer HiRes-120 fidelity model. Therefore, it would be difficult to contribute evidence from *study 1* to add to the findings from *study 4*. In *study 2* results were able to lend evidence to support *study 1* in the concept that better representation of pitch produces better melody recognition with pure tones for CI users via the CIS and n-of-m strategy. Authors also concluded that current CI devices cannot represent complex tone pitch effectively for this CI population. Again, newer strategies have not been proportionally represented in the population for the second study, making it difficult to correlate results of this study to *study 4.* The authors of *Study 3* only makes use of the n-of-m CI strategy and so the objective measure of determining CI performance (which could also help differentiate between CI strategies) is limited to the adult CI population using that particular strategy.

While no evidence exists to identify one current CI strategy as universally superior, there appears to be support for a recommendation of specific modifications for enhanced music perception and appreciation, such as higher stimulus pulse rates and capturing a wider range of fine structure information to increase spectral resolution. However, one common issue that appears in all of these studies relates to the small sample groups available. Small groups within experimental designs lead small power and this may be why there were no differences in the direct comparison study due to the possibility of a small effect size.

Another issue in drawing conclusions from these studies is that music appreciation can be affected by factors apart from CI strategy. Improved spectral resolution is not the only important component for music reproduction. Findings from previous studies have indicated that frequency-pitch misalignment might account for difficulties in music perception for CI users (Cianfrone, Giannantonio, Nardo, Paludetti, Scorpecci, 2011). Differences in cortical and auditory pathway functioning can be a contributor to variable music perception results in CI users (Dorman & Wilson, 2008). Also, research indicates better performance associated with complete electrode insertion depth in the scala tympani (Dorman & Wilson, 2008).

Conclusions and Clinical Implications

In this review, it was made clear that adult CI recipients are not able to perceive and appreciate music as well as normal hearing individuals. Research investigating newer cochlear implant strategies revealed that the FSP strategy may not necessarily be a superior intervention for enhanced music perception in CI users. However, it was determined that more research is needed in this area, and that there may be other factors influencing the ability to perceive music other than the CI strategy. Given the current findings, there is a need for continued research into the improvements in music perception through newer CI interventions. One can conclude at the very least that CI users should be provided with one or more of the newer CIS strategies (such as FSP or HDCIS) in their CI device as a clinical option for enhancing music appreciation.

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