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PERCEPTION OF MUSICAL HARMONY: A CASE STUDY OF ONE COCHLEAR IMPLANT USER AND TWO NORMAL-HEARING SUBJECTS

Contributions:
A Study design/planning
B Data collection/entry
C Data analysis/statistics
D Data interpretation
E Preparation of manuscript
F Literature analysis/search
G Funds collection

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Abstract

Introduction: The perception of musical intervals is a fundamental component of melody and harmony. Intervals can be presented melodically (successive tones) or harmonically (simultaneous tones), with the latter playing a critical role in the perception of consonance and chordal structure. In the chromatic scale, intervals are measured in semitones, and their perceived pleasantness (i.e., consonance or dissonance) is determined by the frequency ratio between them. Cochlear implant (CI) users are likely to perceive harmonic intervals differently from normal-hearing individuals due to technological limitations in transmitting the spectral and temporal complexity of musical sounds. Factors affecting perception of sounds in CI users include placement of the electrode array inside the cochlea and spread of excitation along the auditory nerve.

Case report: To explore differences in how harmonic intervals are perceived, this study presents three case studies of the ranked pleasantness of consonance and dissonance by (1) a normal-hearing individual without musical training; (2) a normal-hearing musician; and (3) a cochlear implant user.

Conclusions: The findings provide a foundation for future investigations into interval perception and have implications for auditory rehabilitation and music-based therapy.

Keywords: cochlear implant • musical intervals • harmonic interval • consonance • dissonance

PERCEPCJA HARMONII MUZYCZNEJ: STUDIUM PRZYPADKU UŻYTKOWNIKA IMPLANTU ŚLIMAKOWEGO I DWÓCH OSÓB Z PRAWIDŁOWYM SŁUCHEM

Streszczenie

Wprowadzenie: Percepcja interwałów muzycznych, czyli odległości między dźwiękami mierzonej w półtonach, stanowi kluczowy element w odbiorze melodii i harmonii. Interwały mogą występować w formie melodycznej (dźwięki następujące po sobie) lub harmonicznej (dźwięki brzmiące jednocześnie), przy czym te drugie odgrywają istotną rolę w odbiorze współbrzmień i akordów. W skali chromatycznej odczuwana przyjemność brzmienia interwałów harmonicznych (określana jako konsonans lub dysonans) wynika z relacji częstotliwości pomiędzy dźwiękami tworzącymi dany interwał. Użytkownicy implantów ślimakowych mogą postrzegać interwały harmoniczne inaczej niż osoby prawidłowo słyszące, ponieważ implanty mają ograniczenia w przekazywaniu złożonej struktury czasowej i widmowej sygnałów muzycznych. Na percepcję dźwięków u użytkowników implantów ślimakowych wpływają różne czynniki, w tym: rozmieszczenie elektrod w ślimaku oraz rozkład pobudzenia nerwu słuchowego.

Opisy przypadków: W niniejszej pracy przedstawiono trzy przypadki, w których dokonano oceny przyjemności brzmienia interwałów harmonicznych: 1) osobę ze słuchem prawidłowym bez wykształcenia muzycznego, 2) muzyka ze słuchem prawidłowym oraz 3) użytkownika implantu ślimakowego.

Wnioski: Uzyskane wyniki stanowią punkt wyjścia do dalszych badań nad percepcją interwałów muzycznych oraz jej potencjalnym znaczeniem w procesie rehabilitacji słuchu i terapii opartej na muzyce.

Słowa kluczowe: implant ślimakowy • interwały muzyczne • interwały harmoniczne • konsonans • dysonans

Introduction

The perception of musical intervals is a fundamental issue in musicology and in how musical sounds are perceived. Intervals, defined as the difference in pitch between two sounds, play a central role in the way melody and harmony are perceived and how musical structure is shaped. The recognition of intervals depends on both the acoustic properties of a sound and on the cognitive experience of the listener [1].

Musical intervals come in two basic forms: melodic, when sounds are presented sequentially in time, and harmonic, when they occur simultaneously. While melodic intervals build melody, the perception of harmonic intervals plays an important role in the perception of harmony, consonance, and chords, which are the foundation of most musical systems – whether classical or popular.

In the chromatic scale, commonly used in music, the ratios of two fundamental frequencies of sounds are measured in semitones, so that 12 semitones correspond to a doubling of frequency. Specific ratios such as the octave (12 semitones) or the pure fifth (7 semitones) are perceived as the most pleasing, while others such as the minor second (1 semitone) or the major seventh (11 semitones) are perceived as the most unpleasant. A list of all the simple intervals within the octave is given in **Table 1**. When two sounds are presented to a listener simultaneously (harmonically), the relationship between their fundamental frequencies (together with cultural exposure) determines how pleasant the composite sound is perceived. Musically, the result is deemed pleasant (consonance) or unpleasant (dissonance) [2,3]. In European-style tonality, dissonance is subjectively harsh, and introduces a tension that requires resolution, i.e., a transition to consonance [4]. Consonances are divided into perfect and imperfect consonances (perfect consonances sound smooth or congruent, while imperfect ones sound sufficiently congruent to not require resolution) [5]. Evaluating simple intervals on a category of pleasantness makes it possible to construct a pattern of harmonic intervals.

Users of cochlear implants (CIs) will tend to experience harmonic intervals differently from individuals with normal hearing. Spitzer et al. [6] demonstrated that the typical pattern of interval perception is less distinct in CI users – specifically, the differences in pleasantness ratings between particular intervals are significantly reduced compared to those of normal-hearing listeners. This altered perception may lead to a musical piece being experienced in a way that diverges from the composer's original intent. Although CIs significantly improve speech understanding, their limited temporal and frequency resolution results in substantially reduced performance in conveying many musical features, particularly melody and harmony [7]. Several factors contribute to the atypical perception of musical intervals in CI users compared to those with acoustic hearing. These include the limited number of electrode channels, electrode interaction, current spread from electrodes, the depth of electrode array insertion, and the specific signal encoding strategy employed [8–11].

While the literature includes numerous studies on melody perception in CI users, considerably less attention has been given to the perception of harmony [12,13]. The aim of this paper is to present three case studies in which the perception of harmonic intervals was examined. We identified three target groups – normal-hearing individuals, normal-hearing musicians, and CI users – and examined

Table 1. Basic musical intervals

Interval	Distance between notes (semitones)	Consonance/dissonance
Perfect unison	0	Perfect consonance
Minor second	1	Dissonance
Major second	2	Dissonance
Minor third	3	Imperfect consonance
Major third	4	Imperfect consonance
Perfect fourth	5	Perfect consonance
Tritone	6	Dissonance
Perfect fifth	7	Perfect consonance
Minor sixth	8	Imperfect consonance
Major sixth	9	Imperfect consonance
Minor seventh	10	Dissonance
Major seventh	11	Dissonance
Perfect octave	12	Perfect consonance

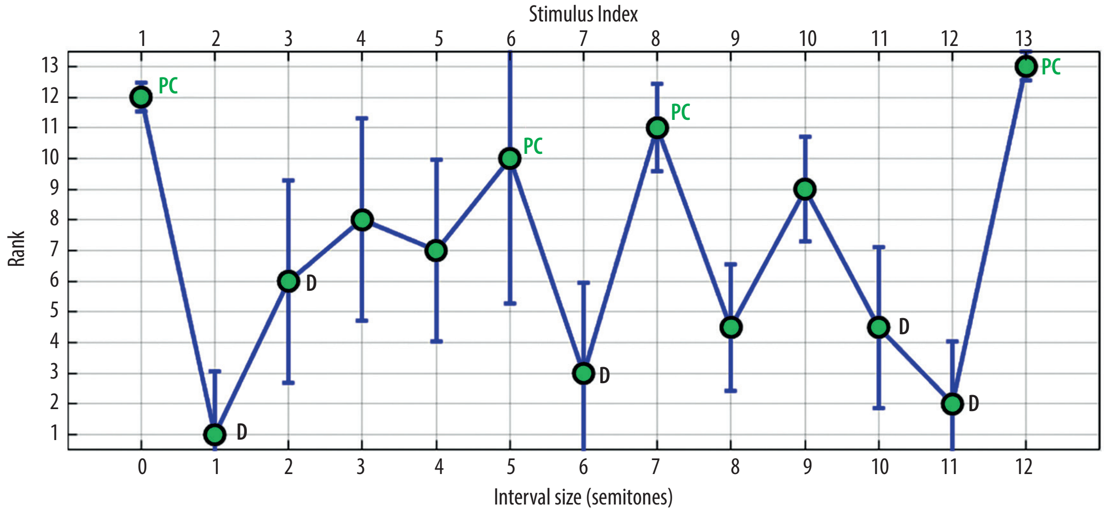

Figure 1. Results for case 1. Pleasantness (rank 1–13, vertical axis) of two harmonically presented tone pairs as gauged by a normal hearing subject. The horizontal axis is the number of semitones between the two tones. PC = perfect consonance; D = dissonance

one case from each of these. An additional objective was to assess the test procedure based on pair comparisons.

Methods

Non-invasive psychoacoustic tests were performed using the PsyWorks 7.1.1 software from Med-El (Innsbruck, Austria). Two harmonic stimuli (intervals "1" and "2") were presented to the listener in sequence and the listener was asked to indicate which one was more pleasant. Each stimulus consisted of two tones presented simultaneously, forming a harmonic interval. In each stimulus, the ratio of fundamental frequencies corresponded to one of 13 different values, ranging from unison (0 semitones) to an octave (12 semitones). The lower tone always had a fundamental frequency of 440 Hz, corresponding to A440 (A4 in musical notation).

The midpoint comparison (MC) procedure, described by Long et al. [14], was used to determine, through pairwise comparisons, the pleasantness of the 13 stimuli. The MC algorithm orders a set of items by iteratively comparing pairs and updating a provisional ranking as more data are collected. Each new tone is first compared with the stimulus located at the midpoint of the current ranking, and the tone pairs are each compared only once per run. Participants are not allowed to respond that two tones are equally pleasant; even if uncertain, they are required to make a choice. This forced-choice design ensures that the algorithm can continuously refine the ordering based on the accumulation of comparison outcomes.

The study was conducted with the approval of the Bioethics Committee at the Institute of Physiology and Pathology of Hearing, Warsaw (No. KB.IFPS 10/2024).

Case reports

Case 1

Case 1 was a 41-year-old male with normal bilateral hearing who underwent the musical interval perception test using earphones. He performed pairwise comparisons of tones generated by the PsyWorks software. In the resulting graph (**Figure 1**), the vertical axis represents the assigned pleasantness score (ranked 1–13).

As shown in **Figure 1**, the perfect consonance (PC) intervals were ranked as the most pleasant. These included the unison (0 semitones), perfect fourth (5 semitones), perfect fifth (7 semitones), and octave (12 semitones), which were assigned ranks between 10 and 13. Other consonant intervals also ranked relatively high: the minor third (3 semitones), major third (4 semitones), minor sixth (8 semitones), and major sixth (9 semitones) received ranks ranging from 4.5 to 9. In contrast, dissonant (D) intervals were ranked much lower: the minor second (1 semitone), major second (2 semitones), tritone (6 semitones), minor seventh (10 semitones), and major seventh (11 semitones) were all assigned ranks between 1 and 6.

Case 2

Case 2 was a 41-year-old female with normal bilateral hearing and a background in formal music education. She was actively engaged in musical activities, particularly the piano. The musical interval perception test was again administered through earphones.

As shown in **Figure 2**, the PC intervals were again ranked as the most pleasant. These included the unison (0 semitones), perfect fourth (5 semitones), perfect fifth (7 semitones), and octave (12 semitones), which were assigned ranks between 9 and 13. Other consonant intervals were also ranked highly: the minor third (3 semitones) and major third (4 semitones) received ranks of 8 and 10 respectively, while the minor sixth (8 semitones) and major sixth (9 semitones) were assigned slightly lower ranks, 4 and 6 respectively. In contrast, D intervals were ranked significantly lower: the minor second (1 semitone), major second (2 semitones), minor seventh (10 semitones), and major seventh (11 semitones) all received ranks between 1 and 5. The tritone (6 semitones), typically considered dissonant, was

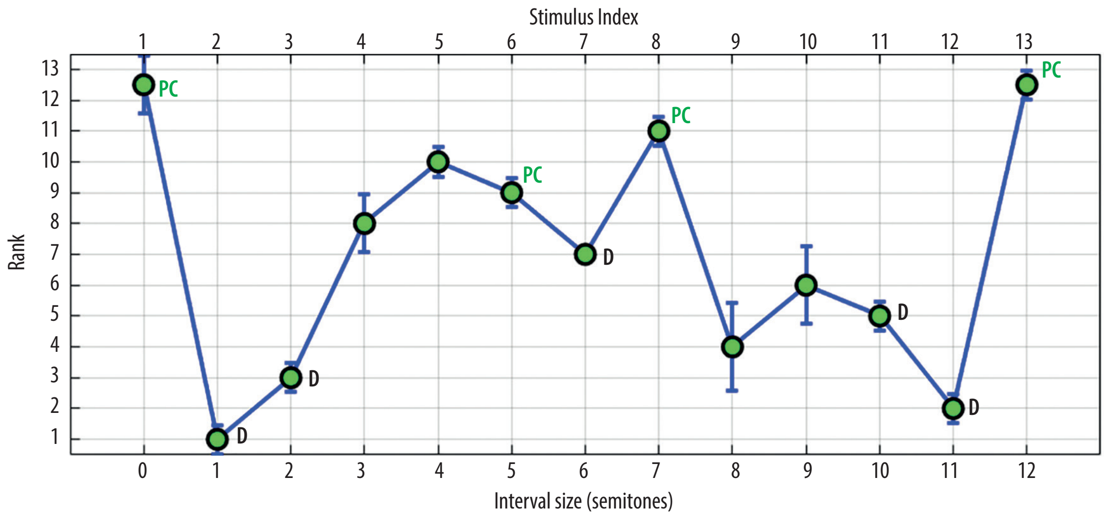

Figure 2. Results for case 2. Pleasantness (rank 1–13) of harmonically presented tone pairs as gauged by a musically trained subject. The horizontal axis is the number of semitones between the two tones. PC, perfect consonance; D, dissonance

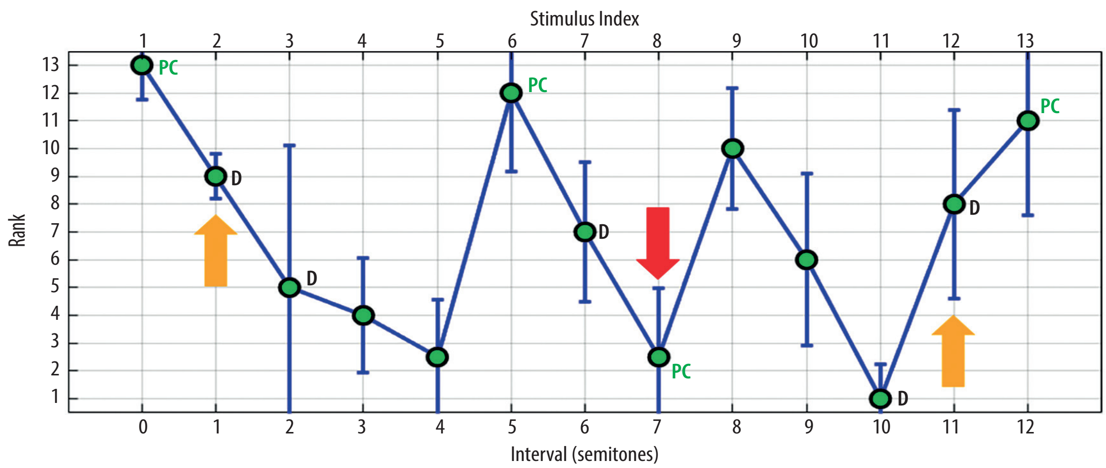

Figure 3. Results for case 3. Pleasantness (rank 1–13) of harmonically presented tone pairs as gauged by a subject having bilateral CIs, with the tones delivered to the right CI. Layout as per previous figures. Scores that differ significantly from those of the normal-hearing individuals in **Figures 1 and 2** (defined as a difference of more than 5 in rank) are highlighted – orange arrows indicate intervals rated significantly higher and red arrows indicate intervals significantly lower

ranked 7. In general, the ranking scores in case 2 showed less variation (smaller standard deviations) than in case 1. This smaller variability may be attributed to the subject's formal ear training and ongoing musical experience.

Case 3

Case 3 was a 36-year-old female with bilateral cochlear implants (Pulsar and Synchrony 2 with Sonnet 2 speech processor from Med-El). The first implant was placed in the right ear at the age of 20; the second was implanted 1 year ago. The FS4 coding strategy was used in both. During testing, auditory signals were delivered to the right implant via a cable connected to the direct audio input of the speech processor, and the results are shown in **Figure 3**.

As shown in **Figure 3**, PC intervals were generally ranked as the most pleasant, with the notable exception of the perfect fifth (7 semitones). The unison (0 semitones), perfect fourth (5 semitones), and octave (12 semitones) were assigned high ranks, in the range of 11–13. In contrast, the perfect fifth of 7 semitones, which is typically ranked highly by normal-hearing individuals, was assigned one of the lowest ranks in this case (2.5). Other consonant intervals, such as the minor third (3 semitones) and major third (4 semitones), also received relatively low ranks (4 and 2.5 respectively), whereas the minor sixth (8 semitones) and major sixth (9 semitones) were ranked more favorably (10 and 6 respectively).

Interestingly, D intervals were rated more pleasant by this CI user compared to normal-hearing listeners. For example, the minor second (1 semitone) is usually ranked as the most unpleasant by normal-hearing individuals, but was placed near the top of the scale at rank 9, while the major second (2 semitones) received a mid-range rank of 5. The most unpleasant interval for the CI user was the minor seventh (10 semitones), which was assigned the lowest rank (1). By way of contrast, among normal-hearing individuals, the major seventh (11 semitones) and the minor second (1 semitone) are typically ranked as the least pleasant intervals.

In **Figure 3**, scores of PC and D that differ significantly from those of normal-hearing individuals (defined as a difference of more than 5 in rank) are highlighted. Orange arrows indicate intervals that were rank significantly higher, and red arrows indicate intervals that received significantly lower rankings.

Discussion

The results of musical interval perception in normal-hearing individuals, as presented in this study, are largely consistent with earlier literature findings [15,16]. They reveal a relatively fixed pattern in the perception of both consonant and dissonant intervals. The smaller variability in judgments observed in the case of the normal-hearing individual with musical training may be attributed to their musical experience and prior ear training. It can be assumed that in the case of musicians, their interval evaluations may be influenced by their personal preferences, not just perceptual differences. The literature indicates that the ability to discriminate and evaluate harmonic intervals improves with musical training. Individuals with such experience demonstrate greater precision in identifying intervals and heightened sensitivity to subtle differences in intonation [15]. In contrast, individuals without musical training tend to rely more on general acoustic properties than on tonal relationships. Interestingly, in this case, the musician ranked the tritone higher (by 4 ranks), which could be because musicians tend to favor tritones more than non-musicians due to their tonal instability and resolution-seeking quality.

The case of the CI user described here shows major deviations in the perception of harmonic intervals compared to the other two normal-hearing individuals. These differences may result from a combination of factors. Technological limitations of the CI – particularly its reduced spectral and temporal resolution – are likely contributors. Additionally, individual-specific factors such as age at implantation, the quality of the electrode–neuron interface, electrode array length and its placement within the cochlea, and neuroplasticity should also be considered [17, 18]. To the authors' knowledge, there is no clear position in the literature as to whether CI users are able to unequivocally perceive dissonance and consonance for harmonic intervals using electric hearing. Brockmeier et al. [19] reported that CI users were able to discriminate musical chords, but discrimination was worse than in normal-hearing listeners. CI users ($n = 31$) and normal-hearing listeners ($n = 67$) had significantly different scores for discrimination of pitch, melody, and chords and for detection and identification of instruments, although no significant differences were observed in scores for the subtests of rhythm discrimination, dissonance evaluation, and emotion evaluation [19]. In contrast, Knobloch et al. [18] reported that CI users were able to discriminate chords, and their preference ratings of selected isolated chords were generally similar to those of normal-hearing listeners. Surprisingly, for the single CI user in this study, the consonant interval of the perfect fifth was ranked very low. We can only speculate that the pleasantness of particular musical intervals perceived through a CI is related to many factors, among which the health of the cochlear nerve (i.e., the survival of neural elements) at the site of excitation, as well as interactions between stimulated electrodes due to the spread of electric current, could play a major role.

In their work, Spitzer et al. [6] assessed the perceived dissonance of harmonic intervals in individuals with single-sided deafness (SSD) who had received a CI ($n = 11$). The study compared subjective pleasantness ratings for intervals presented to the CI ear alone (CI-only listening), the normal-hearing ear (NH-only listening), and both ears simultaneously (NH + CI listening). When listening with the NH ear only, intervals such as the minor second, major second, and major seventh were rated as the least pleasant, whereas the major third, perfect fifth, and octave were rated as the most pleasant. In the CI-only condition, the ratings differed from those of the NH ear and exhibited less variation in pleasantness, resulting in a flatter pattern of responses. Ratings obtained in the NH + CI condition were similar to those from NH-only listening. The authors observed notable asymmetry in interval ratings between ears within individual participants, and only a few showed correlations between their NH-only and CI-only ratings. However, at the group level, mean ratings were highly correlated between NH-only and CI-only conditions ($r = 0.85$, $p < 0.001$), suggesting that relative dissonance was similarly perceived across acoustic and electric hearing. In the present study, the pattern of pleasantness rankings for different intervals under CI-only listening conditions differed noticeably from that observed in individuals with normal hearing. A direct comparison between the current findings and those of Spitzer is limited by significant methodological differences – specifically, the current study employed ordinal pleasantness rankings, whereas Spitzer's work used pleasantness ratings on an analog scale.

Nevertheless, a tentative comparison is possible by relating the ranking patterns from the current study to the z-score–normalized rating patterns reported by Spitzer. This approximation reveals some similarities. For example, in Spitzer's study of electric hearing (CI-only), the major third (4 semitones) received a notably lower rank and lower rating compared to acoustic hearing conditions, an outcome similar to the NH ear of the SSD patients and to our cases 1 and 2.

When considering hearing under acoustic-only conditions, there also appears to be consistency between our studies and those of Spitzer: despite the differing methodologies, dissonant intervals were consistently judged as less pleasant by normal-hearing individuals, both in the ranking-based method used here and the rating-based approach of Spitzer. Yet this similarity did not extend to electric hearing. In our work, the CI user unexpectedly ranked dissonant intervals – the minor second (1 semitone) and the major seventh (11 semitones) – as relatively pleasant. In contrast, Spitzer found that dissonant intervals were rated as unpleasant in both electric and acoustic hearing, suggesting that perception of dissonance under CI stimulation in their SSD cohort more closely resembled normal-hearing patterns. To truly understand whether musical interval perception is more or less the same under electric and acoustic conditions – or whether it differs entirely or depends upon the individual – further research with larger cohorts is necessary. It may be possible to identify specific factors about CI use – such as speech processor settings – that influence musical perception, potentially making it possible to optimize them for better musical appreciation.

An additional aim of our study was to evaluate the test procedure based on pair comparisons. The results appear promising and suggest that this tool may provide a valuable complementary assessment, alongside traditional speech-based tests, to gauge the benefits of cochlear implantation. It may also provide a useful measure for evaluating the effectiveness of post-implantation rehabilitation, including music-based listening training and music therapy interventions. We plan to expand the study to three larger groups: those with normal-hearing but no musical education, professional musicians with normal hearing, and individuals with CIs.

Conclusions

The pattern of musical interval perception observed in the two normal-hearing participants in this study is consistent with patterns previously reported in the literature. The results of the musically experienced individual were characterised by smaller variability in pleasantness rankings, a finding that aligns with other studies showing that musical training enhances perceptual consistency. In contrast, the perception of consonance and dissonance of our CI user deviated markedly from the pattern observed in the other normal-hearing individuals, and this highlights the need for further investigation.

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