

Musical Mistuning Perception and Appraisal in Cochlear Implant Recipients

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Objective: Music is a very crucial art form that can evoke emotions, and the harmonious presence of the human voice in music is an impactful part of this process. As a result, vocals have had some significant effects on contemporary music. The mechanism behind the cochlear implant (CI) recipients perceiving different aspects of music is clear; however, how well they perceive vocal tuning within music it is not well known. Hence, this study evaluated the mistuning perception of CI recipients and compared their performance with normal-hearing (NH) listeners.

Study Design, Setting, and Patients: A total of 16 CI users (7 cisgender men, 9 cisgender women) and 16 sex-matched NH controls with an average age of 30.2 (± 10.9 ; range, 19–53) years and 23.5 (± 6.1 ; range, 20–37) years, respectively, were enrolled in this study. We evaluated the mistuning ability using the mistuning perception test (MPT) and assessed self-perceived music perception and engagement using the music-related quality-of-life questionnaire. Test performance was measured and reported on the item-response theory metric with a z score ranging from -4 to $+4$.

Results: A significant difference in the MPT scores was found between NH and CI recipients, whereas a significant correlation was noted between the music-related quality-of-life questionnaire–frequency subscale and MPT scores. No significant correlations were found between age, CI age, and CI usage duration and MPT performance.

Conclusions: This study revealed that musical mistuning perception is a limitation for CI recipients, similar to previously evaluated aspects of music perception. Hence, it is important to consider this aspect in the assessment of music perception, enjoyment, and music-based auditory interventions in CI recipients, as vocals are paramount in music perception and recreation. The MPT is a convenient and accessible tool for mistuning assessment in CI and hearing-aid users.

Key Words: Cochlear implant—Mistuning perception—Music-related quality of life.

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INTRODUCTION

Despite significant improvements in various auditory aspects with cochlear implant (CI) technology, music remains a challenging concept for CI users. CI recipients have poorer musical perception skills in various aspects including pitch

perception (1–3), melody recognition (4–7), timbre recognition (2,8–11), melodic contour identification (12–14), and dissonance–harmony perception (15,16). Besides the poorer perception, musical enjoyment and appreciation can also be limited (17–20), albeit not as prominent or as consistent as with music perception. Considering that enjoyment is a very individualize and subjective process, factors contributing to music appraisal/enjoyment are a topic of debate. Studies have suggested that previous music experience, various psychoacoustical abilities, residual hearing, and individual differences (e.g., cognitive factors and demographics) may influence music appraisal (21–24). This aspect requires consideration for the perceived benefits of CI recipients, considering the significant relationship between music and quality-of-life (QoL) measurements (25,26).

As a result of the limited music perception and appraisal, researchers and CI manufacturers aimed to overcome this limitation. Various approaches are developed such as different sound processing strategies or changing the features of music before CI processing. Researchers proposed using schemes to reduce spectral complexity (27–30) and remixing music based on the preferences of CI recipients (31–34). In

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Statement of Ethics: This study was presented to the Near East University Ethics Committee in June 2021 under the reference YDU/2021/93-1375. All the participants in this research have received verbal and written information and have been able to ask questions about the study. They willingly signed an informed consent form before starting the trial.

The authors disclose no conflicts of interest.

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various studies, the most consistent and critical finding of previous studies is that CI recipients preferred larger vocals to instrument ratio in songs ranging from 3 to 15 dB (31), 1.92 and 3.82 dB on average (33), and 8–9 dB on average (34,35). This common observation is intriguing considering the importance of human voice and lyrics in modern music. Although research often focuses on singular aspects of music, vocal perception in a busy musical stream is critical. Globally, it is easy to see that listeners listen mostly to music with vocals, with a simple look at data on the current popular music streaming services. Demetriou et al. (36) stated that vocals are a salient component in the minds of listeners and ranked high as a factor for liking a song. Because distinguishing between vocal and instrumental voices is difficult for CI recipients because of limited access to pitch and timbre cues (31), vocal perception in music is worth consideration in this population.

Musical tuning between musical instruments and the human voice is an integral part of music composition and performance. In modern popular and mainstream music, fixed-pitch instruments mostly tuned to equally tempered tuning system are used. In this system, the octave is divided into 12 logarithmically equal pitch classes, and each adjacent pitch is separated by a semitone. Each semitone has a fundamental frequency that is perceptually experienced as a pitch. The various discrete pitch categories can be grouped to create scales that provide a conceptual framework. Unintended deviations from the pitch prescribed by the melody and scale can be perceived as a mistuning (37,38). Normal-hearing (NH) listeners make reliable judgments of mistuning between music and vocals and have an intuitive notion of what sounds correct (39). Although in-tune melodies are theoretically associated with coherent musical intervals and a constant center of tone, singing performances often deviate from such normative expectations. Despite some variabilities in terms of musical tuning and perceived performance quality (38), occasional singers often deviate from 0 to 80 cents when singing (40).

In real life, CI users most often listen to vocal performances accompanied by several instruments. Thus, relationship between musical instruments and vocals may be a significant consideration when evaluating music enjoyment and perception. However, besides the vocal-music ratio studies, the detection of mistuning in vocals has never been evaluated in CI recipients. We believe that it would reflect real-life musical experiences better and comprehensively in CI users when used in conjunction with music appraisal tools, such as questionnaires (41). Thus, this study aimed to investigate the mistuning perception in NH and CI users and compare these skills with their music-related QoL.

METHODS AND MATERIALS

Participants

Sixteen CI users (7 cisgender men, 9 cisgender women) and sex-matched 16 NH controls with an average age of 30.2 (± 10.9 ; range, 19–53) years and 23.5 (± 6.1 ; range, 20–37) years, respectively, participated in this study. CI users were recruited by invitation among individuals who

were attending their regular fitting sessions in the university clinic. The assessment was completed after the CI fitting and free-field audiometric testing. NH was confirmed by type A tympanogram, presence of acoustical reflexes, presence of distortion product otoacoustic emissions (signal-to-noise ratio ≥ 6 dB) in at least three frequency bands tested, and 20 dB or better pure-tone average (between 250 and 8000 Hz) in behavioral audiometry.

The inclusion criteria for CI recipients were as follows: greater than 1 year of CI use, postlingual hearing loss (before 6 yr of age), age greater than 12 years during the test, and normal auditory nerve and cochlear anatomy. All participants could communicate orally and gain speech perception scores after CI use (monosyllabic word recognition score range, 96–56%). Participants were excluded if they had any formal music education beyond regular music lessons in grade school or additional mental and neurological disorders. Detailed information of CI recipients is listed in Table 1. Hearing loss age and implantation age were also collected. All CI recipients had bilateral sensorineural hearing loss (four frequency pure-tone average of 80 dB HL or worse) preoperatively, they were all unilateral users, and five of them had hearing aids in their contralateral ear (bimodal users). Eleven CI recipients without hearing aids in their contralateral ear have no useful (pure-tone thresholds not obtained or very high, e.g., 100–110 dB) acoustic hearing in their contralateral ears.

The protocol of this study was approved by the ethics committee, and informed written consent was obtained from all the participants.

Mistuning Perception Assessment

Several tests are available for the assessment of mistuning (42–45). Even though they all provide reliable and useful measurements, most of them do not use real musical excerpts. The process usually involves removing the pitch from the complex tones of various musical textures. Larrouy-Maestri et al. (46) proposed to use real musical excerpts that would be more beneficial and better to reflect daily music-listening experiences in mistuning perception assessment. They have developed a new assessment method called the mistuning perception test (MPT) to measure mistuning perception ability using popular musical excerpts (46). They conducted a validity and reliability study in NH listeners using 37 musical pieces with various pitch relations between vocals and instruments.

The mistuning ability was evaluated using the MPT, which was developed and validated recently by Larrouy-Maestri et al. (46). The MPT is an adaptive two-alternative forced choice task testing the discrimination between a pitch-shifted and unaltered version of the same short musical excerpts. Participants were instructed to determine the “out-of-tune” excerpt between the two. Each test started with detailed instructions and a two-trial training session, followed by the real test that included 15 trials. The test performance was measured and reported on the item-response theory metric with a z score ranging from -4 to 4 . Testing completed in an acoustically treated room at a comfortable listening level.

TABLE 1. Demographics, cochlear implant information, and behavioral audiometry results

Demographics		Free-Field Hearing Thresholds (dB)										WRS (%)			
Code	Sex	Age (yr)	CI Dur. (yr)	CI Age (yr)	CI Ear	CI Processor	Bimodal	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	6000 Hz	8000 Hz	WRS (%)
CI1	M	40	7	33	Left	Nucleus 6	Y	30	30	30	30	30	35	30	56
CI2	F	28	15	13	Right	Nucleus 6	N	35	40	30	30	35	40	55	88
CI3	F	25	9	16	Right	Nucleus 6	N	35	25	20	30	35	35	50	56
CI4	F	27	7	20	Right	Rondo 2	Y	30	35	35	20	30	30	30	80
CI5	F	49	9	40	Right	Sonnet	N	25	25	25	25	25	25	15	56
CI6	F	20	6	14	Right	Rondo 1	Y	35	35	35	35	35	30	30	76
CI7	M	24	6	18	Right	Nucleus 6	N	25	25	35	30	25	30	30	76
CI8	F	21	8	13	Right	Nucleus 7	N	25	25	20	15	25	25	10	76
CI9	M	44	4	40	Left	Kanso 1	N	30	30	20	25	25	25	40	76
CI10	M	53	7	46	Right	Saphyr Neo	N	45	45	35	35	40	40	40	68
CI11	F	23	8	15	Right	Rondo 1	Y	30	40	35	35	40	40	40	72
CI12	F	19	3	16	Right	Nucleus 7	N	35	25	30	35	25	35	25	76
CI13	M	31	14	17	Right	Nucleus 7	Y	35	40	40	35	35	40	40	56
CI14	M	36	4	32	Right	Rondo 1	N	25	25	20	20	20	20	20	84
CI15	M	23	7	16	Left	Opus 2	N	30	25	25	15	20	20	10	44
CI16	F	20	5	15	Right	Nucleus 6	N	30	30	40	35	35	40	40	64
Mean		30.2	7.4	22.8				31.3	31.3	30.0	27.5	30.0	31.9	31.6	69.0

CI indicates cochlear implant; Dur, duration; F, female; M, male; N, no; WRS, word recognition score; Y, yes.

An MPT was conducted in a double-walled audiometric booth (Industrial Acoustics Company Inc., Illinois, USA). The sound intensity was set at 65 dBA, and the test stimuli were presented on a computer connected to a Madsen Astera audiometer (Otometrics, Natus Medical, Denmark) with a single JBL Control One Loudspeaker (JBL; Harman International, Stamford, CT) positioned 1 m away with 0-degree azimuth and elevation from the horizontal plane of participants' ears.

Music-Related QoL Assessment

Music-related QoL (MuRQoL) assessment was conducted using the questionnaire developed by Dritsakakis et al. (41), as a measure to guide music rehabilitation for adult CI recipients, and it was adapted and validated for the Turkish language and culture by Akbulut et al. (47). MuRQoL is a 5-point Likert-type scale with two subsections on the frequency scale (FS) and importance scale (IS). Each subsection has music perception and music engagement parts with 11 and 7 items each, respectively. Thus, each FS and IS have a total of 18 items. Points obtained from each section were converted to a 0 to 100 scale; that is, 1, 2, 3, 4, and 5 were converted to 0, 25, 50, 75, and 100, respectively. Converted scores were added up for FS and IS separately and divided by 18, which is the number of items in each subscale that provided the final scores used for the analysis. Because the MuRQoL scale was developed for CI recipients and our aim was to assess the relationship between music-related QoL and mistuning perception in CI recipients, only the CI group completed the MuRQoL scale.

Data Analysis

Statistical analyses were performed using R Statistical Software (www.r-project.org). Given the limited number of patients, a normal distribution could not be assumed, and the Mann-Whitney *U* test was used to compare the MPT for the CI and NH groups. Spearman correlation coefficients were calculated between MPT and MuRQoL FS and IS. The results were considered significant when the *p* values were less than 0.05.

RESULTS

MPT Group Differences

Detailed MPT results for the CI and NH groups are presented in Table 2. On average, the CI and NH groups scored -0.12 and -1.18, respectively, and the difference was significant (*p* < 0.001). Although the difference was significant between the groups, the *z* score range (CI group, 3.55; NH group, 3.13) and variability measured with standard deviation (CI group, 0.83; NH group, 0.92) were comparable. Although not included in the statistical analysis because of a small sample size (*n* = 5), bimodal users scored better on the MTP (*z* score = -0.91) than unilateral CI recipients (*z* score = -1.35).

MuRQoL, Demographics, and MPT Scores

MuRQoL-FS and IS scores for the CI group are presented in Table 3. A significant correlation was found between the MuRQoL-FS and MPT results for the CI group (*r* = 0.515;

TABLE 2. *Mistuning perception test results and descriptive statistics for the cochlear implant and normal-hearing groups*

NH group (n = 16)	Mean		-0.1165	
	95% Confidence interval for mean	Lower bound	-0.6068	Upper bound
	Median		-0.1205	
	Variance		0.847	
	SD		0.92018	
	Minimum		-1.41	
	Maximum		1.72	
CI group (n = 16)	Mean		-1.1794	
	95% Confidence interval for mean	Lower bound	-1.6214	
		Upper bound	-0.7373	
	Median		-1.1210	
	Variance		0.688	
	SD		0.82959	
	Minimum		-3.34	
	Maximum		0.21	

CI indicates cochlear implant; NH, normal-hearing; SD, standard deviation.

$p = 0.030$). However, no significant correlation was found between the MuRQoL-IS and MPT results, even though the correlation coefficient indicated medium-strength correlation ($r = 0.438$; $p = 0.058$). Moreover, no significant correlation was found between chronological age ($p = 0.198$), CI age ($p = 0.094$), and CI usage duration ($p = 0.200$) and MPT scores.

DISCUSSION

In this study, we assessed the musical mistuning perception abilities of NH and CI listeners, and our results revealed a poorer performance in the latter. This finding is not surprising, considering that NH listeners have better auditory perception abilities, typical auditory development, and, in most cases, richer and more comprehensive music-listening experiences. Moreover, tuning perception in music requires both a good pitch perception to track the fundamental frequency provided by vocals and auditory stream segregation ability to perceive relative pitch changes (48). NH listeners have better pitch and auditory stream segregation abilities than CI listeners.

Arguably, the most fundamental limitation stems from limited and less precise (compared with NH) neural excitation within the cochlea and the lack of temporal fine structure in the CI processing. Modern CI systems use only 12 to 22 spectral channels to transmit a wide range of frequencies,

and because of channel interactions, the actual number of independent channels is lower. The primary clue for pitch perception is provided by fundamental frequency (F0) and harmonics of the signal (49,50). F0 and harmonics are unlikely to be resolved with such poor frequency selectivity (51,52). Other factors such as the electrode position and neural spread rate of spiral ganglion cells (53), amount of channel interaction, and propagation of neural excitation (54) can also affect the accuracy of temporal pitch extraction. Up to 30 channels are required to achieve close tone recognition accuracy in CIs, and even more channels are required for music perception (55,56). In electrical hearing, multichannel CI users can perceive musical pitch in two ways. The primary mechanism is based on rapid temporal fluctuation in electrical impulses. Modern CIs generally do not change the stimulation rate in speech-processing strategies, except for the fine structure coding strategy, initiated by Med-EL, which changes the instantaneous stimulation rate at the apical electrodes (57–59).

In this study, we also assessed the music-related QoL with the MuRQoL scale, which reflects the attitudes of CI users toward music. The CI recipient scores were comparable to previous reports, and a significant moderate correlation was found between FS and MPT. Accordingly, it can be said that CI listeners' self-perceived music perception abilities and engagement were positively associated with mistuning perception. However, no significant correlation was found between MPT results and IS (even though a medium-low strength correlation coefficient was obtained); thus, the “importance” and “value” CI listeners attach to musical activities are not related to mistuning perception. This difference between self-perceived abilities and importance can be explained with the subjective effect on a person's life regardless of their hearing status and/or auditory abilities. Besides data obtained from previous studies, a weak or nonexistent relationship was found between music perception abilities and music-listening habits in CI recipients (19,20). Common sense also suggests that perception and enjoyment or importance are two different things in life. Our findings provide a scientific and reasonable conclusion on the very nature of music.

TABLE 3. *Music-related quality of life—frequency scale and importance scale subscale scores for cochlear implant group*

MuRQoL Scores	MuRQoL Scores			
	Minimum	Maximum	Mean	SD
Music perception—FS	2.46	4.91	3.68	0.81
Music engagement—FS	2.14	4.86	3.72	0.76
Total score—FS	2.33	4.89	3.70	0.73
Music perception—IS	2.00	5.00	4.18	0.81
Music engagement—IS	2.00	5.00	3.93	0.94
Total score—IS	2.00	5.00	4.09	0.84

FS indicates frequency scale; IS, importance scale; MuRQoL, music-related quality of life; SD, standard deviation.

This study showed that chronological age, implantation age, and duration of CI usage were not related to the MPT results. In many studies, musical perception may be related to music education, enjoyment, and exposure rather than implant age and duration of implant use (54,55,58). However, in one study, the duration of CI use plays a role in the development of music perception (54,55,58). Essentially, Giraud et al. (54) point to improved auditory discrimination skills in more experienced CI users and stated that electrical stimulation causes experience-related changes in auditory cortex functions after implantation (60). Plastic changes in the auditory cortex may also explain individual auditory system differences to fully use implant-provided information (60). Thus, based on our study, whether a relationship exists between MPT and other demographic characteristics should be investigated comprehensively with a structured sample.

Future Implications

Although CIs have structural limitations for musical perception, the effect of music education on MPT should also be examined. Individuals who did not have a musical education were included in our study. Studies have stated that music education influences singing and pitch perception of CI users. For example, Rocca (61) stated that they teach instruments to many children older than 7 years who are CI users. They found that many of these children could distinguish tones and semitones on their instruments, primarily through the listening skills they have acquired by training themselves to interpret the sounds they heard through their implants. According to Fuller et al. (62), their findings may imply that music education programs and/or device enhancements that improve music perception can improve QoL and hearing ability. In the light of this information, based on our study, differences in performance in individuals with CI can be examined by evaluation before and after music education with the MPT. Because MPT consists of frequently heard musical pieces, it can give a holistic result in understanding the tonal awareness of CI users.

Thanks to technological innovations with CI, wireless audio streaming with Bluetooth has become easier. With the direct transfer of music to the ear, better mistuning perception skills can develop with a better sound quality. In this case, musical enjoyment can increase. Thus, future generations will be more successful in recognizing musical differences with these technological innovations. However, audiologists should inform the family to encourage the use of this technology. Accordingly, for a better QoL standard, musical MPT can be used in CI recipients.

Limitations

Bimodal users performed better in the MPT, but we could not conduct a statistical comparison with adequate power because of the small sample size. Bimodal users are less frequent than unilateral CI recipients in our university clinic; thus, only five bimodal users participated in this study. Considering the previous studies on the benefit of bimodal hearing on various psychoacoustic tasks (10,63,64), inclusion of more bimodal participants could provide a better understanding in the present study.

CONCLUSIONS

Structural harmony between musical instruments and especially in human voice/vocals is a fundamental part of music, but the present findings showed that CI recipients experience limitations in perceiving such harmony. Considering the importance of vocals in music perception and enjoyment, mistuning assessment should be considered in music-based auditory tests and interventions in CI recipients.

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REFERENCES

- Cooper WB, Tobey E, Loizou PC. Music perception by cochlear implant and normal hearing listeners as measured by the Montreal Battery for Evaluation of Amusia. *Ear Hear* 2008;29:618–26.
- Drennan WR, Rubinstein JT. Music perception in cochlear implant users and its relationship with psychophysical capabilities. *J Rehabil Res Dev* 2008;45:779–89.
- McDermott HJ, McKay CM. Musical pitch perception with electrical stimulation of the cochlea. *J Acoust Soc Am* 1997;101:1622–31.
- Gfeller K, Turner C, Mehr M, et al. Recognition of familiar melodies by adult cochlear implant recipients and normal-hearing adults. *Cochlear Implants Int* 2002;3:29–53.
- Gfeller K, Turner C, Oleson J, et al. Accuracy of cochlear implant recipients on pitch perception, melody recognition, and speech reception in noise. *Ear Hear* 2007;28:412–23.
- Looi V, McDermott H, McKay C, Hickson L. *Pitch discrimination and melody recognition by cochlear implant users*. Paper presented at: International Congress Series VIII International Cochlear Implant Conference, Indianapolis, Indiana, United States, 10–13 May 2004, Amsterdam, The Netherlands; 2004.
- Yüksel M, Çiprut A. Music and psychoacoustic perception abilities in cochlear implant users with auditory neuropathy spectrum disorder. *Int J Pediatr Otorhinolaryngol* 2020;131:109865.
- Gfeller K, Witt S, Adamek M, et al. Effects of training on timbre recognition and appraisal by postlingually deafened cochlear implant recipients. *J Am Acad Audiol* 2002;13:132–45.
- Heng J, Cantarero G, Elhilali M, Limb CJ. Impaired perception of temporal fine structure and musical timbre in cochlear implant users. *Hear Res* 2011;280(1–2):192–200.
- Kong Y-Y, Mullangi A, Marozeau J. Timbre and speech perception in bimodal and bilateral cochlear-implant listeners. *Ear Hear* 2012;33:645–59.
- Macherey O, Delpierre A. Perception of musical timbre by cochlear implant listeners: A multidimensional scaling study. *Ear Hear* 2013;34:426–36.
- Galvin JJ III, Fu Q-J, Oba SI. Effect of a competing instrument on melodic contour identification by cochlear implant users. *J Acoust Soc Am* 2009;125:EL98–EL103.
- Galvin JJ III, Fu Q-J, Shannon RV. Melodic contour identification and music perception by cochlear implant users. *Ann N Y Acad Sci* 2009;1169:518–33.
- Galvin JJ 3rd, Fu QJ, Nogaki G. Melodic contour identification by cochlear implant listeners. *Ear Hear* 2007;28:302–19.
- Caldwell MT, Jiradejvong P, Limb CJ. Impaired perception of sensory consonance and dissonance in cochlear implant users. *Otol Neurotol* 2016;37:229–34.
- Zimmer V, Verhey JL, Ziese M, Böckmann-Barthel M. Harmony perception in prelingually deaf, juvenile cochlear implant users. *Front Neurosci* 2019;13:466.
- Drennan WR, Oleson JJ, Gfeller K, et al. Clinical evaluation of music perception, appraisal and experience in cochlear implant users. *Int J Audiol* 2015;54:114–23.
- PrevotEAU C, Chen SY, Lalwani AK. Music enjoyment with cochlear implantation. *Auris Nasus Larynx* 2018;45:895–902.

19. Wright R, Uchanski RM. Music perception and appraisal: Cochlear implant users and simulated cochlear implant listening. *J Am Acad Audiol* 2012;23:350–65.
20. Yüksel M, Atlıgan A, Çıprut A. Music listening habits and music perception abilities of prelingually deafened adolescent cochlear implant recipients. *J Am Acad Audiol* 2020;31:740–5.
21. Gfeller K, Christ A, John K, Witt S, Mehr M. The effects of familiarity and complexity on appraisal of complex songs by cochlear implant recipients and normal hearing adults. *J Music Ther* 2003;40:78–112.
22. Gfeller K, Oleson J, Knutson JF, et al. Multivariate predictors of music perception and appraisal by adult cochlear implant users. *J Am Acad Audiol* 2008;19:120–34.
23. Gfeller K, Witt S, Mehr MA, Woodworth G, Knutson J. Effects of frequency, instrumental family, and cochlear implant type on timbre recognition and appraisal. *Ann Otol Rhinol Laryngol* 2002;111:349–56.
24. Looi V, Gfeller K, Driscoll V. Music appreciation and training for cochlear implant recipients: A review. *Semin Hear* 2012;33:307–34.
25. Dritsakis G, van Besouw RM, O'Meara A. Impact of music on the quality of life of cochlear implant users: A focus group study. *Cochlear Implants Int* 2017;18:207–15.
26. Lassalletta L, Castro A, Bastarrica M, et al. Does music perception have an impact on quality of life following cochlear implantation? *Acta Otolaryngol* 2007;127:682–6.
27. Buyens W, Moonen M, Wouters J, Dijk BV. *A model for music complexity applied to music preprocessing for cochlear implants*. Kos, Greece: Paper presented at: 25th European Signal Processing Conference (EUSIPCO); 2017.
28. Gauer J, Krymova E, Belomestny D, Martin R. *Spectral complexity reduction of music signals for cochlear implant users based on subspace tracking*. Paper presented at: 2019 27th European Signal Processing Conference (EUSIPCO); September 2–6; 2019.
29. Nagathil A, Schlattmann J-W, Neumann K, Martin R. Music complexity prediction for cochlear implant listeners based on a feature-based linear regression model. *J Acoust Soc Am* 2018;144:1–10.
30. Nagathil A, Weihs C, Martin R. Spectral complexity reduction of music signals for mitigating effects of cochlear hearing loss. *IEEE/ACM Trans Audio Speech Lang Proc* 2015;24:445–58.
31. Buyens W, van Dijk B, Moonen M, Wouters J. Music mixing preferences of cochlear implant recipients: A pilot study. *Int J Audiol* 2014;53:294–301.
32. Gajęcki T, Nogueira W. Deep learning models to remix music for cochlear implant users. *J Acoust Soc Am* 2018;143:3602–15.
33. Pons J, Janer J, Rode T, Nogueira W. Remixing music using source separation algorithms to improve the musical experience of cochlear implant users. *J Acoust Soc Am* 2016;140:4338–49.
34. Tahmasebi S, Gajęcki T, Nogueira W. Design and evaluation of a real-time audio source separation algorithm to remix music for cochlear implant users. *Front Neurosci* 2020;14:434.
35. Limb CJ, Mo J, Jiradejvong P, Jiam NT. The impact of vocal boost manipulations on musical sound quality for cochlear implant users. *Laryngoscope* 2022; 10.1002. Online ahead of print.
36. Demetrio AM, Jansson A, Kumar A, Bittner RM. *Vocals in music matter: the relevance of vocals in the minds of listeners*. Paper presented at: Proceedings of the 19th ISMIR Conference, Paris, France, September 23–27, 2018; 2018.
37. Thompson WF. Intervals and scales. In: Deutsch D, ed. *The Psychology of Music*. 3rd ed. Oxford, UK: Elsevier; 2013.
38. Warren RA, Curtis ME. The actual vs. predicted effects of intonation accuracy on vocal performance quality. *Music Percept Interdiscipl J* 2015;33:135–46.
39. Larrouy-Maestri P, Magis D, Grabenhorst M, Morsomme D. Layman versus professional musician: Who makes the better judge? *PloS One* 2015;10:e0135394.
40. Pfordresher PQ, Larrouy-Maestri P. On drawing a line through the spectrogram: How do we understand deficits of vocal pitch imitation? *Front Hum Neurosci* 2015;9:271.
41. Dritsakis G, van Besouw RM, Kitterick P, Verschuur CA. A music-related quality of life measure to guide music rehabilitation for adult cochlear implant users. *Am J Audiol* 2017;26:268–82.
42. Hutchins S, Roquet C, Peretz I. The vocal generosity effect: how bad can your singing be? *Music Percept* 2012;30:147–59.
43. Larrouy-Maestri P, Lévêque Y, Schön D, Giovanni A, Morsomme D. The evaluation of singing voice accuracy: A comparison between subjective and objective methods. *J Voice* 2013;27:259.e1–5.
44. Furma A, Ross J. Production and perception of musical intervals. *Music Percept* 2006;23:331–44.
45. Warrier CM, Zatorre RJ. Influence of tonal context and timbral variation on perception of pitch. *Percept Psychophys* 2002;64:198–207.
46. Larrouy-Maestri P, Harrison PMC, Müllensiefen D. The mistuning perception test: A new measurement instrument. *Behav Res Methods* 2019;51:663–75.
47. Akbulut AA, Çıprut A, Akdeniz E, Batman Ç. Translation and validation of the music-related quality of life questionnaire for adults with cochlear implant in Turkish language. *Eur Arch Otorhinolaryngol* 2021;279:685–93.
48. Oxenham AJ. Pitch perception and auditory stream segregation: Implications for hearing loss and cochlear implants. *Trends Amplif* 2008;12:316–31.
49. Xu L, Pfingst BE. Relative importance of temporal envelope and fine structure in lexical-tone perception. *J Acoust Soc Am* 2003;114(6 Pt 1): 3024–7.
50. Xu L, Tsai Y, Pfingst BE. Features of stimulation affecting tonal-speech perception: implications for cochlear prostheses. *J Acoust Soc Am* 2002; 112:247–58.
51. Townshend B, White RL. Reduction of electrical interaction in auditory prostheses. *IEEE Trans Biomed Eng* 1987;34:891–7.
52. Zeng FG. Temporal pitch in electric hearing. *Hear Res* 2002;174(1–2): 101–6.
53. Moore BC. Coding of sounds in the auditory system and its relevance to signal processing and coding in cochlear implants. *Otol Neurotol* 2003;24:243–54.
54. Giraud AL, Truy E, Frackowiak R. Imaging plasticity in cochlear implant patients. *Audiol Neurootol* 2001;6:381–93.
55. Kong YY, Cruz R, Jones JA, Zeng FG. Music perception with temporal cues in acoustic and electric hearing. *Ear Hear* 2004;25:173–85.
56. Kong YY, Zeng FG. Temporal and spectral cues in Mandarin tone recognition. *J Acoust Soc Am* 2006;120(5 Pt 1):2830–40.
57. Arnoldner C, Riss D, Brunner M, et al. Speech and music perception with the new fine structure speech coding strategy: Preliminary results. *Acta Otolaryngol* 2007;127:1298–303.
58. Riss D, Arnoldner C, Baumgartner WD, Kaider A, Hamzavi JS. A new fine structure speech coding strategy: Speech perception at a reduced number of channels. *Otol Neurotol* 2008;29:784–8.
59. Wang W, Zhou N, Xu L. Musical pitch and lexical tone perception with cochlear implants. *Int J Audiol* 2011;50:270–8.
60. Sandmann P, Kegel A, Eichele T, et al. Neurophysiological evidence of impaired musical sound perception in cochlear-implant users. *Clin Neurophysiol* 2010;121:2070–82.
61. Rocca C. A different musical perspective: improving outcomes in music through habilitation, education, and training for children with cochlear implants. *Semin Hear* 2012;33:425–33.
62. Fuller C, Free R, Maat B, Başkent D. Self-reported music perception is related to quality of life and self-reported hearing abilities in cochlear implant users. *Cochlear Implants Int* 2022;23:1–10.
63. Cullington HE, Zeng F-G. Comparison of bimodal and bilateral cochlear implant users on speech recognition with competing talker, music perception, affective prosody discrimination and talker identification. *Ear Hear* 2011;32:16–30.
64. Illg A, Bojanowicz M, Lesinski-Schiedat A, Lenarz T, Büchner A. Evaluation of the bimodal benefit in a large cohort of cochlear implant subjects using a contralateral hearing aid. *Otol Neurotol* 2014; 35:e240–4.