

University of Groningen

The effect of music on auditory perception in cochlear-implant users and normal-hearing listeners

Fuller, Christina Diechina

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version

Publisher's PDF, also known as Version of record

Publication date:

2016

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Fuller, C. D. (2016). *The effect of music on auditory perception in cochlear-implant users and normal-hearing listeners*. [Thesis fully internal (DIV), University of Groningen]. Rijksuniversiteit Groningen.

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

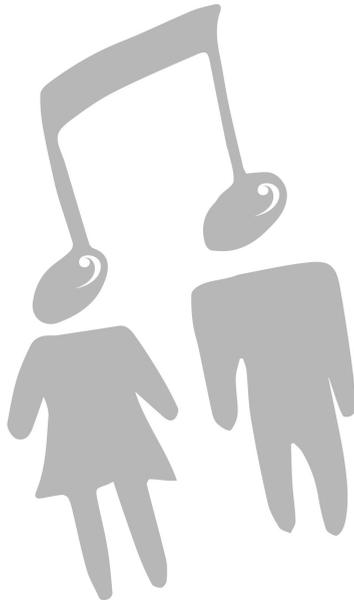
Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Chapter 1

Introduction to the thesis



This thesis focuses on music and speech perception in cochlear implants (CIs). Music and speech are fundamental human communication methods, and are part of every society in the world. Humans begin learning speech and music at a very early age, and both can be extensively trained (especially necessary for music). Both are temporally organized acoustical signals (Asaridou and McQueen 2013). While there are many similarities between speech and music (e.g., pitch and timbre), there are also fundamental differences. Music amongst others targets an emotional response that may differ across listeners, while speech is meant to convey less ambiguous information. Music is structured according to basic elements of pitch, rhythm, timbre, and melody. In terms of lexical meaning (“what is said”), speech is structured in terms of phonemes, syllables, words and sentences. However, speech can also convey indexical cues (“who said it”) and prosodic cues (“how it was said”) via changes in pitch, timbre and rhythm cues. Speech and music can also be explicitly combined (e.g., sung musical lyrics). Good speech perception is possible using primarily temporal envelope cues (Shannon et al., 1995), but music requires fine-structure cues for harmonic pitch perception (see Fig. 2) (Smith, Delgutte, and Oxenham 2002; Shannon, Fu, and Galvin 2004).

A growing body of research has been directed at understanding neural correlates of music and speech, as well as similarities and differences between speech and music perception. There is also great interest in possible cross-domain effects of long-term musical experience and/or musical training on speech perception (Micheyl et al. 2006; Zatorre 2013; Kraus, Zatorre, and Strait 2014; Herholz and Zatorre 2012; Patel 2014). These studies have been largely conducted with normal hearing (NH) musicians and non-musicians. In NH listeners, the auditory system is intact and capable of perceiving both envelope and fine-structure cues. However, hearing-impaired listeners may not have the same access to fine-structure information, which might limit perception of music and speech where pitch and timbre cues are important. This is especially true for persons who use a CI, an auditory prosthesis to restore hearing to profoundly deaf individuals. Originally designed to convey speech information (i.e., slowly varying spectral and temporal cues), CIs do not effectively transmit fine-structure cues. As a result, music perception is often difficult, as is speech perception, especially in adverse listening conditions (Shannon, Fu, and Galvin 2004). This thesis describes the subjective and behavioral perception of music and pitch-mediated speech in CI users and in NH listeners. We also explored possible advantages of musical experience and training on music and speech perception.

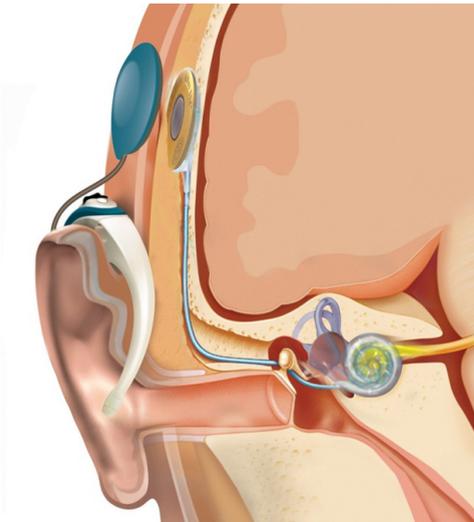
COCHLEAR IMPLANTS

Cochlear implants are auditory prostheses that restore hearing in profoundly deaf individuals by direct stimulation of the auditory neurons using electrodes that are surgically placed within the cochlea. The CI thus provides electrical hearing instead of normal, acoustical

hearing. As of 2012, there were 324,200 CI recipients worldwide according to the U.S Food and Drug Administration (National Institute on Deafness and Other Communication Disorder 2011), with approximately 5500 CI recipients in the Netherlands.

CIs were developed to investigate whether electrical stimulation of the auditory nerve could replace acoustical hearing and thereby restore hearing to severely deaf people. The first CIs were single-channel implants, and were implanted into humans in the 1970s (Clark (2003); p15-22). Surprisingly, these patients were capable of some word recognition, but only in combination with lip-reading (Waltzman and Roland 2011). These early studies also showed that the CI improved patients' quality of life (QoL) and the quality of their speech production (Waltzman and Roland 2011). Following these promising early outcomes, CI technology quickly improved, introducing multi-channel stimulation, better electrode designs, and signal processing strategies to reduce noise and improve the transmission of key speech features. As CI technology improved, so did CI outcomes (Blamey et al. 2013). With multi-channel implants, CI users were often capable of audio-only open-set speech recognition. Accordingly, the CI has become accepted worldwide as an effective intervention for post-lingually deafened adults and in many countries, for pre-lingually deafened young children.

SOUND PERCEPTION WITH COCHLEAR IMPLANTS



Despite the success of the CI, there is great variability in patient outcomes and all CI users have difficulty in challenging listening conditions, such as speech understanding in noise, perception of pitch cues in speech, music perception, etc. (Looi, Gfeller, and Driscoll 2012; Gfeller et al. 2008; Fetterman and Domico 2002; Kong et al. 2009; Kong and Carlyon 2010). Some of this variability may be implant-related; some may be patient-related (Blamey et al. 2013; Lazard et al. 2012; Başkent et al. 2016).

FIGURE 1. A cochlear implant.

http://hearinghealthfoundation.org/lib/sitefiles/images/magazines/CIs_Figure_2_Summer_2012.jpg

Typical CI hardware (see Figure 1) consists of a microphone, a signal processor either body-worn or behind-the ear, a transmitter coil, a receiver coil, and an array of implanted

electrodes. The microphone picks up the acoustical signal, which is then optimized and digitized by the signal processor. Signal processing and pre-processing can differ across implant manufacturers. Typically, the acoustic signal is band-pass filtered into frequency analysis bands. The temporal envelope (changes in amplitude over time; see Figure 2) from each band is extracted and used to modulate pulse trains delivered to assigned electrodes. The signal is digitized and transmitted to the receiver coil, which decodes the signal and

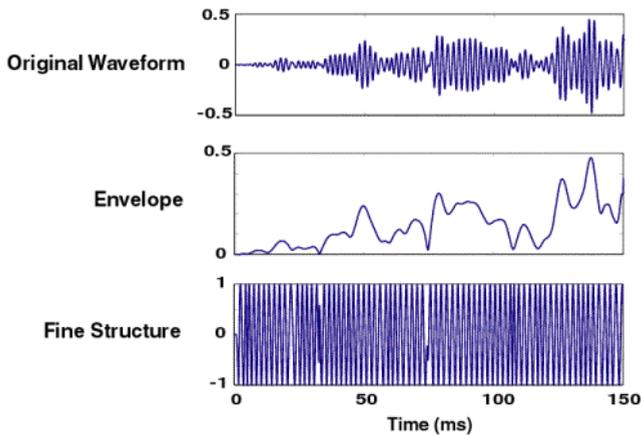


FIGURE 2: The original waveform, the temporal envelope and the fine structure of an acoustical signal.

<https://research.meei.harvard.edu/chimera/images/motiva1.gif>

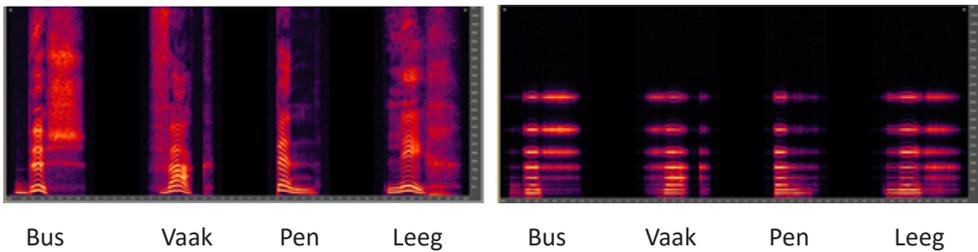


FIGURE 3 (also used in chapter 8) Spectrograms for Dutch monosyllabic words “Bus,” “Vaak,” “Pen,” and “Leeg” (“Bus,” “Often,” “Pen,” and “Empty” in English), shown for unprocessed speech (left panel) or with an 8-channel CI simulation (right panel).

delivers electrical current to the implanted electrodes, thereby directly stimulating the auditory neurons in the spiral ganglia lining the cochlear duct. CI electrode arrays currently have 12 to 22 intra-cochlear electrodes, much fewer than the number of critical bands available for NH listeners to process the wide range of acoustic sounds. Figure 3 shows a spectrogram of unprocessed speech (left panel) and speech processed by an 8-channel CI simulation. The electric dynamic range is also much smaller than in acoustic hearing, making

noise problematic for CIs. In typical CI signal processing, spectro-temporal fine structure information is discarded. For most CI users, pitch is perceived via temporal envelope information and changes in the coarse spectral envelope. Due to the limited number of electrodes (12-22) and the interactions among electrodes associated with current spread, complex pitch perception (which requires harmonic frequency components to be resolved) is not presently possible with CIs. Mean frequency discrimination thresholds can be as low as 0.4 semitones for NH listeners, but as high as 5.5 semitones for CI users (Wang, Zhou, and Xu 2011). This poor pitch resolution can greatly limit CI users' melodic pitch perception (Galvin, Fu, and Nogaki 2007; Kong et al. 2004) and perception of vocal emotion or voice gender (Xin, Fu, and Galvin 2007; Gilbers et al. 2015; Gaudrain and Baskent 2015; Fuller et al. 2014c). Beyond implant-related limitations, patient-related factors may further limit perception of the information transmitted by the CI. Duration of deafness, etiology of deafness, patterns of nerve survival, health of auditory neurons, deafness-related changes in cognitive processing may differ across patients, and may explain some of the variability in CI outcomes (Başkent et al. 2016; Blamey et al. 2013)

Thus, implant- and patient-related factors may limit CI users' perception of music and speech. The nature of the listening task and type of stimuli may also play a factor in how well one performs with the CI. In clinical practice, CI performance is only assessed for speech perception, and is often measured using identification of simple sentences and/or monosyllabic words in quiet. CI performance can deteriorate in the presence of steady noise, and further worsens in competing speech or fluctuating maskers (Friesen et al. 2001; Nelson and Jin 2004; Stickney et al. 2004; Nogaki, Fu, and Galvin 2007; Fu and Nogaki 2005). Voice gender identification depends strongly on perception of pitch cues, and can thus be difficult for CI users (Fuller et al. 2014c; Xin, Fu, and Galvin 2007; Wilkinson et al. 2013; Fu, Chinchilla, and Galvin 2004). Vocal emotion identification similarly depends strongly on voice pitch cues and is therefore difficult for many CI users (Xin, Fu, and Galvin 2007; Gilbers et al. 2015). Melodic pitch perception has been shown in many studies to be difficult for CI users (e.g., Gfeller et al. 2007; Galvin et al. 2012; Galvin, Fu, and Nogaki 2007). Thus, different listening tasks and stimuli may elicit further differences among CI users, and better define perceptual limits for "real-life" listening conditions.

MUSIC AND CIs

Music is a fundamental, powerful, and often pleasurable form of human communication (Koelsch et al. 2006; Zatorre and Salimpoor 2013; Salimpoor et al. 2009). Moreover, music is considered to be the second most important acoustical signal after speech by CI users (Boucher and Bryden 1997; Drennan and Rubinstein 2008; Salimpoor et al. 2009; Patel 2014). In many ways, music is a more complicated signal than speech. In terms of perception,

fine-structure cues are considered as more important for music and envelope cues more important for speech (Smith, Delgutte, and Oxenham 2002).

There can be great variability among CI users' music enjoyment (subjective measures) and music perception (behavioral measures), but an association between music enjoyment and perception is not a given. Especially music enjoyment seems to be affected by more factors than just perception quality. For example, pre-lingually deafened and early implanted CI children greatly enjoy music, even if their melodic pitch perception is poor (Trehub, Vongpaisal, and Nakata 2009). Post-lingually deafened adult CI users often rate the way music sounds with their CI as poorer than previously experienced with NH (Trehub, Vongpaisal, and Nakata 2009; Gfeller et al. 2000b; Lassaletta et al. 2008). While music perception may not improve, music enjoyment may improve in time (especially with training) and may greatly benefit CI users. For patients with Parkinson's disease and/or dementia, music therapy and training have been shown to improve QoL (Hilliard 2003; Walworth et al. 2008).

Given the potential benefits of music listening and training, efforts to improve music enjoyment could be beneficial in the rehabilitation/or training of CI users. Theoretically, music enjoyment may be increased by improving music perception, as better music perception may provide more enjoyment. Perception of musical pitch, melody and timbre has been shown to be poorer in CI users than in NH listeners (Drennan et al. 2015; Drennan and Rubinstein 2008; McDermott 2004; Limb and Roy 2014). However, musical rhythm is perceived with almost the same accuracy in CI users as in NH listeners (Gfeller, et al. 2007, Kong, et al. 2004). While 4 spectral channels can provide good understanding of speech in quiet, more than 48 spectral channels are needed for melody recognition, and many more channels for good sound quality (Shannon, Fu, and Galvin 2004). Music training may help to compensate for some of the coarse and/or distorted cues provided by the CI. It remains a great challenge in research and development of CIs to sufficiently increase the quality of the signal transmitted to support good pitch perception, which is needed for good music perception.

MUSICIAN EFFECT

Music is a potent acoustical stimulus that can communicate emotions and have positive effects on QoL in NH people. Long-term musical training can also enhance the perception of some acoustical signals. A number of perceptual advantages in musicians have been observed, such as enhanced decoding of emotion in a vocal sound (Wong et al. 2007; Musacchia, Strait, and Kraus 2008; Strait et al. 2009; Besson, Chobert, and Marie 2011), better perception of voicing cues in speech and pitch cues in speech and music (Schon, Magne, and Besson 2004; Thompson, Schellenberg, and Husain 2004; Chartrand and Belin 2006), and better speech understanding in noise (Parbery-Clark et al. 2009; Kraus and

Chandrasekaran 2010). In these studies, these advantages were mostly attributed to long-term musical training. This ‘musician effect’ is especially interesting as it implies a possible cross-domain transfer of learning from music training to speech perception in NH.

There are different theories regarding the source of the musician effect. One theory is that musicians have better overall pitch perception, suggesting a musician advantage at the lower levels of the auditory system that makes it easier to differentiate the acoustic cues in complex signals (Micheyl et al. 2006; Besson et al. 2007; Oxenham 2008; Deguchi et al. 2012). Another theory is that musicians have a better higher-level processing (e.g., better use of auditory attention, better short- and/or long-term auditory memory) that leads to improved use of cognitive mechanisms for auditory perception and discrimination (Bialystok and Depape 2009; Besson, Chobert, and Marie 2011; Moreno et al. 2011; Barrett et al. 2013).

The areas of auditory perception where musicians seem to show an advantage over non-musicians are precisely the areas in which CI users experience difficulties, and most involve pitch perception. As discussed above, there is great variability in CI users’ music enjoyment and perception, as well as great variability in challenging speech perception tasks (e.g., vocal emotion identification, speech-on-speech masking, and voice gender identification). For post-lingually deafened CI users, having music experience before implantation may have partially contributed to this variability. For all CI users music training after implantation may help to improve music and speech perception.

AUDITORY TRAINING IN CI USERS

Most current CI rehabilitation programs are focused on speech perception and production. For post-lingually deafened adults, much of the adaptation to the CI occurs during the first 6-12 months of use, peaking approximately 3.5 years after implantation (Blamey et al. 2013; Rouger et al. 2007). Most CI centers offer a three-month rehabilitation program, after which CI users must adapt via daily exposure to different sounds. Speech training has been shown to be effective in improving CI users’ speech perception in quiet and in noise, even after many years of previous experience with their device (Fu, Nogaki, and Galvin III 2005; Stacey et al. 2010; Oba, Fu, and Galvin 2011; Fu and Galvin 2008; Benard and Baskent 2013).

The benefits of music training in CI users have received less attention, as speech perception has long been the main outcome for cochlear implantation. Music training in adult and pediatric CI users has been shown to improve melodic contour identification, timbre recognition, and complex melody recognition (Fu et al. 2015; Galvin et al. 2012; Galvin, Fu, and Nogaki 2007; Yucel, Sennaroglu, and Belgin 2009; Gfeller et al. 2002b; Gfeller et al. 2000b). These previous studies have focused on within-domain (i.e., music perception only) learning and neural plasticity. In this thesis, we explored the possibility of a cross-

domain transfer of learning: that training with music could improve both music and speech perception. A previous pilot study by Patel (2014) with two CI users showed a small effect of music training on perception of speech in noise and prosody in words, suggesting some possibility of cross-domain learning with music training.

OUTLINE OF THE THESIS

In this thesis, the perception of music and the effect of music training on auditory perception in CI users and NH listeners were investigated to answer the following research questions:

1. *Can long-term music experience lead to better perception of the degraded signals provided by the CI? If so, this would suggest that music training may benefit perception of degraded signals provided by CIs.*
2. *Can training after implantation benefit CI users' speech and music perception?*
3. *Which music training methods are most effective in CI users?*

The thesis is composed of three parts to systematically explore the research questions listed above:

1. *Assessment of perception of music and pitch-mediated speech stimuli in CI users*
2. *The musician effect in NH listeners and CI users*
3. *The effect of musical training and music therapy in CI users*

1. Assessment of the perception of music and pitch-mediated speech stimuli in CI users

First, we assessed the difficulties that CI users experience in enjoying music and perceiving music and pitch-mediated speech, using subjective and behavioral measures. We also investigated potential links between these difficulties to general speech perception and QoL. This first part of the thesis consists of four studies. The first two investigated self-reported music perception and enjoyment in two groups of CI users: 1) early-deafened, late-implanted CI users, and 2) post-lingually deafened CI users. We also examined how self-reported music perception and enjoyment relates to speech perception and QoL. The third and fourth studies further investigated two separate elements; voice gender and vocal emotion perception by NH and CI listeners. In the voice gender categorization study, we manipulated the voice characteristics to gradually change from a female to a male talker, and the task was to identify the speaker's gender. In the vocal emotion identification study, we used a nonsense word produced in four emotions (anger, sadness, joy, and relief), and the task was to identify the correct emotion.

2. *The musician effect in NH listeners and CI users*

Here, we investigated whether active musical training might contribute to a better perception of speech, pitch-mediated speech, and music in CI users and NH musicians and non-musicians. Musicians were used as a model of long-term music training. This part of the thesis consists of three studies. The first study investigated the effect of CI users' music experience and training before implantation on speech perception after implantation. The second and third studies aimed to investigate whether the musician effect persists under conditions of reduced spectro-temporal resolution as experienced by CI users. The second study measured perception of word and sentence intelligibility in quiet and in noise, vocal emotion identification, voice gender categorization, and melodic contour identification in NH musicians and non-musicians. The third study investigated the musician effect in NH subjects' voice gender categorization while listening to unprocessed acoustical stimuli and CI simulations.

3. *The effect of music therapy and music training in CI users*

Here, we directly investigated the effects of music therapy and music training on a group of CI users. This was a prospective, feasibility training study in post-lingually deafened, adult CI users. Outcomes for three different training methods (individualized music training, group music therapy, and non-musical training) were compared in terms of speech intelligibility, music perception, perception of pitch-mediated speech, and QoL. CI users were tested before and after six weeks of training.

REFERENCES

- Asaridou, S. S., and J. M. McQueen. 2013. Speech and music shape the listening brain: Evidence for shared domain-general mechanisms.
- Barrett, K. C., R. Ashley, D. L. Strait, and N. Kraus. 2013. Art and science: How musical training shapes the brain. *Frontiers in Psychology* 4 (Oct 16): 713.
- Başkent, D., E. Gaudrain, T.N. Tamati, and A. Wagner. 2016. Perception and psychoacoustics of speech in cochlear implant users. . In *Scientific foundations of audiology.*, eds. A. T. Cacace, E. de Kleine, A. Holt and P. van Dijk.
- Benard, M. R., and D. Başkent. 2013. Perceptual learning of interrupted speech. *PLoS One* 8 (3): e58149.
- Besson, M., J. Chobert, and C. Marie. 2011. Transfer of training between music and speech: Common processing, attention, and memory. *Frontiers in Psychology* 2 (May 12): 94.
- Besson, M., D. Schon, S. Moreno, A. Santos, and C. Magne. 2007. Influence of musical expertise and musical training on pitch processing in music and language. *Restorative Neurology and Neuroscience* 25 (3-4): 399-410.
- Bialystok, E., and A. M. Depape. 2009. Musical expertise, bilingualism, and executive functioning. *Journal of Experimental Psychology* 35 (2) (Apr): 565-74.
- Blamey, P., F. Artieres, D. Başkent, F. Bergeron, A. Beynon, E. Burke, N. Dillier, et al. 2013. Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants: An update with 2251 patients. *Audiology & Neuro-Otology* 18 (1): 36-47.
- Boucher, R., and M. P. Bryden. 1997. Laterality effects in the processing of melody and timbre. *Neuropsychologia* 35 (11) (Nov): 1467-73.
- Chartrand, J. P., and P. Belin. 2006. Superior voice timbre processing in musicians. *Neuroscience Letters* 405 (3) (Sep 25): 164-7.
- Clark, G. 2003. *Cochlear implants: Fundamentals and applications*. AIP series in modern acoustics and signal processing. New York: AIP Press/Springer.
- Deguchi, C., M. Boureau, M. Sarlo, M. Besson, M. Grassi, D. Schön, and L. Colombo. 2012. Sentence pitch change detection in the native and unfamiliar language in musicians and non-musicians: Behavioral, electrophysiological and psychoacoustic study. *Brain Research* 1455 : 75-89.
- Dorman, M. F., P. C. Loizou, and D. Rainey. 1997. Simulating the effect of cochlear-implant electrode insertion depth on speech understanding. *The Journal of the Acoustical Society of America* 102 (5): 2993-6.
- Drennan, W. R., J. J. Oleson, K. Gfeller, J. Crosson, V. D. Driscoll, J. H. Won, E. S. Anderson, and J. T. Rubinstein. 2015. Clinical evaluation of music perception, appraisal and experience in cochlear implant users. *International Journal of Audiology* 54 (2) (Feb): 114-23.
- Drennan, W. R., and J. T. Rubinstein. 2008. Music perception in cochlear implant users and its relationship with psychophysical capabilities. *Journal of Rehabilitation Research and Development* 45 (5): 779-89.
- Fetterman, B. L., and E. H. Domico. 2002. Speech recognition in background noise of cochlear implant patients. *Otolaryngology-Head and Neck Surgery* 126 (3) (Mar): 257-63.
- Friesen, L. M., R. V. Shannon, D. Başkent, and X. Wang. 2001. Speech recognition in noise as a function of the number of spectral channels: Comparison of acoustic hearing and cochlear implants. *The Journal of the Acoustical Society of America* 110 (2) (Aug): 1150-63.
- Fu, Q. J., S. Chinchilla, and John J. Galvin. 2004. The role of spectral and temporal cues in voice gender discrimination by normal-hearing listeners and cochlear implant users. *Journal of the Association for Research in Otolaryngology* 5 (3): 253-60.
- Fu, Q. J., J. J. Galvin, X. Wang, and J. L. Wu. 2015. Benefits of music training in mandarin-speaking pediatric cochlear implant users. *Journal of Speech, Language, and Hearing Research* 58 (1): 163-9.
- Fu, Q. J., and G. Nogaki. 2005. Noise susceptibility of cochlear implant users: The role of spectral resolution

- and smearing. *Journal of the Association for Research in Otolaryngology* 6 (1): 19-27.
- Fu, Q. J., G. Nogaki, and J. J. Galvin III. 2005. Auditory training with spectrally shifted speech: Implications for cochlear implant patient auditory rehabilitation. *Journal of the Association for Research in Otolaryngology* 6 (2): 180-9.
 - Fu, Q. J., and J. J. Galvin 3rd. 2008. Maximizing cochlear implant patients' performance with advanced speech training procedures. *Hearing Research* 242 (1-2) (Aug): 198-208.
 - Fuller, C. D., E. Gaudrain, J. N. Clarke, J. J. Galvin, Q. J. Fu, R. H. Free, and D. Başkent. 2014. Gender categorization is abnormal in cochlear implant users. *Journal of the Association for Research in Otolaryngology : JARO* 15 (6) (Dec): 1037-48.
 - Galvin, J. J., E. Eskridge, S. Oba, and Q. J. Fu. 2012. Melodic contour identification training in cochlear implant users with and without a competing instrument. Paper presented at Seminars in hearing, .
 - Galvin, J. J., 3rd, Q. J. Fu, and G. Nogaki. 2007. Melodic contour identification by cochlear implant listeners. *Ear and Hearing* 28 (3) (Jun): 302-19.
 - Audrain, E., and D. Başkent. 2015. Factors limiting vocal-tract length discrimination in cochlear implant simulations. *The Journal of the Acoustical Society of America* 137 (3) (Mar): 1298-308.
 - Gfeller, K., A. Christ, J. F. Knutson, S. Witt, K. T. Murray, and R. S. Tyler. 2000. Musical backgrounds, listening habits, and aesthetic enjoyment of adult cochlear implant recipients. *Journal of the American Academy of Audiology* 11 (7) (Jul-Aug): 390-406.
 - Gfeller, K., J. Oleson, J. F. Knutson, P. Breheny, V. Driscoll, and C. Olszewski. 2008. Multivariate predictors of music perception and appraisal by adult cochlear implant users. *Journal of the American Academy of Audiology* 19 (2) (Feb): 120-34.
 - Gfeller, K., C. Turner, J. Oleson, X. Zhang, B. Gantz, R. Froman, and C. Olszewski. 2007. Accuracy of cochlear implant recipients on pitch perception, melody recognition, and speech reception in noise. *Ear and Hearing* 28 (3) (Jun): 412-23.
 - Gfeller, K., S. Witt, M. Adamek, M. Mehr, J. Rogers, J. Stordahl, and S. Ringgenberg. 2002. Effects of training on timbre recognition and appraisal by postlingually deafened cochlear implant recipients. *Journal of the American Academy of Audiology* 13 (3) (Mar): 132-45.
 - Gilbers, S., C. Fuller, D. Gilbers, M. Broersma, M. Goudbeek, R. Free, and D. Başkent. 2015. Normal-hearing listeners' and cochlear implant users' perception of pitch cues in emotional speech. *I-Perception* 6 (5): 0301006615599139.
 - erholz, S. C., and R. J. Zatorre. 2012. Musical training as a framework for brain plasticity: Behavior, function, and structure. *Neuron* 76 (3) (Nov 8): 486-502.
 - Hilliard, R. E. 2003. The effects of music therapy on the quality and length of life of people diagnosed with terminal cancer. *Journal of Music Therapy* 40 (2) (Summer): 113-37.
 - Koelsch, S., T. Fritz, K. Müller, and A. D. Friederici. 2006. Investigating emotion with music: An fMRI study. *Human Brain Mapping* 27 (3): 239-50.
 - Kong, Y. Y., and R. P. Carlyon. 2010. Temporal pitch perception at high rates in cochlear implants. *The Journal of the Acoustical Society of America* 127 (5) (May): 3114-23.
 - Kong, Y. Y., R. Cruz, J. A. Jones, and F. G. Zeng. 2004. Music perception with temporal cues in acoustic and electric hearing. *Ear and Hearing* 25 (2) (Apr): 173-85.
 - Kong, Y. Y., J. M. Deeks, P. R. Axon, and R. P. Carlyon. 2009. Limits of temporal pitch in cochlear implants. *The Journal of the Acoustical Society of America* 125 (3) (Mar): 1649-57.
 - Kraus, N., and B. Chandrasekaran. 2010. Music training for the development of auditory skills. *Nature Reviews. Neuroscience* 11 (8) (Aug): 599-605.
 - Kraus, N., R. J. Zatorre, and D. L. Strait. 2014. Editors' introduction to hearing research special issue: Music: A window into the hearing brain. *Hearing Research* 308 (Feb): 1.

- Lassaletta, L., A. Castro, M. Bastarrica, R. Perez-Mora, B. Herran, L. Sanz, M. J. de Sarria, and J. Gavilan. 2008. Musical perception and enjoyment in post-lingual patients with cochlear implants. *Acta Otorrinolaringologica Espanola* 59 (5) (May): 228-34.
- Lazard, D. S., C. Vincent, F. Venail, P. Van de Heyning, E. Truy, O. Sterkers, P. H. Skarzynski, et al. 2012. Pre-, per- and postoperative factors affecting performance of postlinguistically deaf adults using cochlear implants: A new conceptual model over time. *PLoS One* 7 (11): e48739.
- Limb, C. J., and A. T. Roy. 2014. Technological, biological, and acoustical constraints to music perception in cochlear implant users. *Hearing Research* 308 (Feb): 13-26.
- Looi, V., K. Gfeller, and V. Driscoll. 2012. Music appreciation and training for cochlear implant recipients: A review. *Seminars in Hearing* 33 (4) (Nov 1): 307-34.
- McDermott, H. J. 2004. Music perception with cochlear implants: A review. *Trends in Amplification* 8 (2): 49-82.
- Micheyl, C., K. Delhommeau, X. Perrot, and A. J. Oxenham. 2006. Influence of musical and psychoacoustical training on pitch discrimination. *Hearing Research* 219 (1-2) (Sep): 36-47.
- Moreno, S., E. Bialystok, R. Barac, E. G. Schellenberg, N. J. Cepeda, and T. Chau. 2011. Short-term music training enhances verbal intelligence and executive function. *Psychological Science* 22 (11) (Nov): 1425-33.
- Musacchia, G., D. Strait, and N. Kraus. 2008. Relationships between behavior, brainstem and cortical encoding of seen and heard speech in musicians and non-musicians. *Hearing Research* 241 (1-2) (Jul): 34-42.
- National Institute on Deafness and Other Communication Disorder. 2011. "Cochlear implants". *NIH Publication no. 11-4798 (2013-11-01)*.
- Nelson, P. B., and S. H. Jin. 2004. Factors affecting speech understanding in gated interference: Cochlear implant users and normal-hearing listeners. *The Journal of the Acoustical Society of America* 115 (5): 2286-94.
- Nogaki, G., Q. J. Fu, and J. J. Galvin 3rd. 2007. Effect of training rate on recognition of spectrally shifted speech. *Ear and Hearing* 28 (2) (Apr): 132-40.
- Oba, S. I., Q. J. Fu, and J. J. Galvin 3rd. 2011. Digit training in noise can improve cochlear implant users' speech understanding in noise. *Ear and Hearing* 32 (5) (Sep-Oct): 573-81.
- Oxenham, A. J. 2008. Pitch perception and auditory stream segregation: Implications for hearing loss and cochlear implants. *Trends in Amplification* 12 (4) (Dec): 316-31.
- Parbery-Clark, A., E. Skoe, C. Lam, and N. Kraus. 2009. Musician enhancement for speech-in-noise. *Ear and Hearing* 30 (6) (Dec): 653-61.
- Patel, A. D. 2014. Can nonlinguistic musical training change the way the brain processes speech? the expanded OPERA hypothesis. *Hearing Research* 308 (Feb): 98-108.
- Rouger, J., S. Lagleyre, B. Fraysse, S. Deneve, O. Deguine, and P. Barone. 2007. Evidence that cochlear-implanted deaf patients are better multisensory integrators. *Proceedings of the National Academy of Sciences of the United States of America* 104 (17) (Apr 24): 7295-300.
- Salimpoor, V. N., M. Benovoy, G. Longo, J. R. Cooperstock, and R. J. Zatorre. 2009. The rewarding aspects of music listening are related to degree of emotional arousal. *PLoS One* 4 (10) (Oct 16): e7487.
- Schon, D., C. Magne, and M. Besson. 2004. The music of speech: Music training facilitates pitch processing in both music and language. *Psychophysiology* 41 (3) (May): 341-9.
- Shannon, R. V., Q. J. Fu, and J. Galvin 3rd. 2004. The number of spectral channels required for speech recognition depends on the difficulty of the listening situation. *Acta Oto-Laryngologica. Supplementum* (552) (552) (May): 50-4.
- Shannon, R. V., F. G. Zeng, V. Kamath, J. Wygonski, and M. Ekelid. 1995. Speech recognition with primarily temporal cues. *Science (New York, N.Y.)* 270 (5234) (Oct 13): 303-4.
- Smith, Zachary M., Bertrand Delgutte, and Andrew J. Oxenham. 2002. Chimaeric sounds reveal dichotomies in auditory perception. *Nature* 416 (6876): 87-90.

- Stacey, P. C., C. H. Raine, G. M. O'Donoghue, L. Tapper, T. Twomey, and A. Q. Summerfield. 2010. Effectiveness of computer-based auditory training for adult users of cochlear implants. *International Journal of Audiology* 49 (5) (May): 347-56.
- Stickney, G. S., F. G. Zeng, R. Litovsky, and P. Assmann. 2004. Cochlear implant speech recognition with speech maskers. *The Journal of the Acoustical Society of America* 116 (2) (Aug): 1081-91.
- Strait, D. L., N. Kraus, E. Skoe, and R. Ashley. 2009. Musical experience promotes subcortical efficiency in processing emotional vocal sounds. *Annals of the New York Academy of Sciences* 1169 (Jul): 209-13.
- Thompson, W. F., E. G. Schellenberg, and G. Husain. 2004. Decoding speech prosody: Do music lessons help? *Emotion (Washington, D.C.)* 4 (1) (Mar): 46-64.
- Trehub, S. E., T. Vongpaisal, and T. Nakata. 2009. Music in the lives of deaf children with cochlear implants. *Annals of the New York Academy of Sciences* 1169 (Jul): 534-42.
- Waltzman, Susan B., and J. Thomas Roland. 2011. *Cochlear implants*. Thieme, New York, 2nd edition.
- Walworth, D., C. S. Rumana, J. Nguyen, and J. Jarred. 2008. Effects of live music therapy sessions on quality of life indicators, medications administered and hospital length of stay for patients undergoing elective surgical procedures for brain. *Journal of Music Therapy* 45 (3) (Fall): 349-59.
- Wang, W., N. Zhou, and L. Xu. 2011. Musical pitch and lexical tone perception with cochlear implants. *International Journal of Audiology* 50 (4): 270-8.
- Wilkinson, E. P., O. Abdel-Hamid, J. J. Galvin, H. Jiang, and Q. J. Fu. 2013. Voice conversion in cochlear implantation. *The Laryngoscope* 123 (S3): S29-43.
- Wong, P. C., E. Skoe, N. M. Russo, T. Dees, and N. Kraus. 2007. Musical experience shapes human brainstem encoding of linguistic pitch patterns. *Nature Neuroscience* 10 (4) (Apr): 420-2.
- Xin, Luo, Q. J. Fu, and J. J. Galvin 3rd. 2007. Vocal emotion recognition by normal-hearing listeners and cochlear implant users. *Trends in Amplification* 11 (4) (Dec): 301-15.
- Yucel, Esra, Gonca Sennaroglu, and Erol Belgin. 2009. The family oriented musical training for children with cochlear implants: Speech and musical perception results of two year follow-up. *International Journal of Pediatric Otorhinolaryngology* 73 (7): 1043-52.
- Zatorre, R. J. 2013. Predispositions and plasticity in music and speech learning: Neural correlates and implications. *Science (New York, N.Y.)* 342 (6158) (Nov 1): 585-9.
- Zatorre, R. J., and V. N. Salimpoor. 2013. From perception to pleasure: Music and its neural substrates. *Proceedings of the National Academy of Sciences of the United States of America* 110 Suppl 2 (Jun 18): 10430-7.

Part one:

***Assessment of the perception of music and
pitch-mediated speech stimuli in
cochlear-implant users***

