Hearing Research 308 (2014) 13–26

Contents lists available at SciVerse ScienceDirect

Hearing Research

journal homepage: www.elsevier.com/locate/heares

Review

Technological, biological, and acoustical constraints to music perception in cochlear implant users

Charles J. Limb [a,b,*], Alexis T. Roy [a]

[a] Department of Otolaryngology-Head and Neck Surgery, Johns Hopkins Hospital, Baltimore, MD, USA
[b] Peabody Conservatory of Music, Johns Hopkins University, Baltimore, MD, USA

ARTICLE INFO

Article history:
Received 17 January 2013
Received in revised form
4 April 2013
Accepted 22 April 2013
Available online 7 May 2013

ABSTRACT

Despite advances in technology, the ability to perceive music remains limited for many cochlear implant users. This paper reviews the technological, biological, and acoustical constraints that make music an especially challenging stimulus for cochlear implant users, while highlighting recent research efforts to overcome these shortcomings. The limitations of cochlear implant devices, which have been optimized for speech comprehension, become evident when applied to music, particularly with regards to inadequate spectral, fine-temporal, and dynamic range representation. Beyond the impoverished information transmitted by the device itself, both peripheral and central auditory nervous system deficits are seen in the presence of sensorineural hearing loss, such as auditory nerve degeneration and abnormal auditory cortex activation. These technological and biological constraints to effective music perception are further compounded by the complexity of the acoustical features of music itself that require the perceptual integration of varying rhythmic, melodic, harmonic, and timbral elements of sound. Cochlear implant users not only have difficulty perceiving spectral components individually (leading to fundamental disruptions in perception of pitch, melody, and harmony) but also display deficits with higher perceptual integration tasks required for music perception, such as auditory stream segregation. Despite these current limitations, focused musical training programs, new assessment methods, and improvements in the representation and transmission of the complex acoustical features of music through technological innovation offer the potential for significant advancements in cochlear implant-mediated music perception.

This article is part of a Special Issue entitled <Music: A window into the hearing brain>.

1. Introduction

Cochlear implants (CI) have been remarkably successful in providing speech perception to the deaf population throughout the world (Clark, 2008). Postlingually deafened CI users routinely achieve high performance on language tests (Gifford et al., 2008; Lalwani et al., 1998) and deaf children implanted at an early age usually develop excellent spoken language skills (Leigh et al., 2013), with placement into mainstream educational schooling (Francis et al., 1999; Govaerts et al., 2002). Yet, the auditory world consists of many other sounds that differ acoustically from spoken language and do not share the high redundancy of speech signals. Of all auditory stimuli, perception of music represents one of the greatest challenge for implant-mediated listening (Limb, 2006), and high-level perception of music is rarely attained through conventional CI technology. There are numerous factors that contribute to the difficulties in CI-mediated music perception. Here we review the technological, biological, and acoustical constraints that limit music perception in CI users. While music may of course serve as a form of entertainment and aesthetic communication, it should be emphasized that music is approached here as arguably the most complex auditory stimulus in existence. As such, the study of how we perceive music—or struggle to do so in the case of individuals with CIs—is an ideal approach to examine how the human peripheral and central nervous systems interact to understand sensory input of remarkable complexity and abstraction more broadly.

2. Technological constraints: limitations of the cochlear implant device

A substantial amount of implant-related degradation takes place during the conversion of acoustic sound into a series of

* Corresponding author. 720 Rutland Ave., Ross 826, Baltimore, MD 21215, USA.
E-mail address: climb@jhmi.edu (C.J. Limb).

0378-5955/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.heares.2013.04.009

electrical impulses that stimulate the auditory nerve. See Fig. 1. This degradation of signal fidelity contributes fundamentally to a wide-range of music perception deficits for CI users (Brockmeier et al., 2011; Donnelly et al., 2009; Kang et al., 2009; Ping et al., 2012). CIs have been developed and primarily optimized to transmit the relevant acoustic cues of speech. Consequently, immediate difficulties occur when the device must represent the acoustical properties of music that exceed those of speech in terms of spectral, temporal, and timbral complexity, as well as dynamic range.

Of all of the individual elements of music, CIs demonstrate severe limitations in pitch representation that have widespread consequences for accurate music perception, since pitch relationships comprise the basis for melodic and harmonic relationships in music. *Pitch* is defined here as the subjective correlate to a tone's fundamental frequency. Pitch information is conveyed to the auditory system using both spatial cues (known as place pitch) and temporal cues (known as rate pitch). In CI-mediated pitch perception, both place pitch and rate pitch mechanisms are impaired.

2.1. Disruption of place pitch mechanisms

Modern multi-channel CI devices convey pitch information by employing electrode place maps that are tonotopically organized. Through the use of bandpass filtering into a series of channels (each covering a specified frequency range), the CI processor separates the composite acoustic input into several frequency components. Lower frequency portions of the signal are sent to more apical electrodes while higher frequencies are sent to more basal electrodes, in an effort to distribute electrical input according to the intrinsic tonotopic map within the cochlea. In comparison to normal hearing, however, the implant only contains (at most) 22 physical electrodes meant to compensate for the functional loss of 3500 inner hair cells. The CI device simply cannot convey the finely graded, frequency-specific information normally transmitted to auditory nerve fibers by inner hair cells. Furthermore, the incoming acoustic signal is bandpass filtered to emphasize speech cues, such that only a frequency range of around ~200 Hz to ~8500 Hz is transmitted (exact ranges depend on the CI device manufacturer and individual patient settings). In addition to pitch resolution being impoverished within this transmitted frequency range, the removal of high and low frequencies from the acoustic input also negatively impacts musical sound quality for many CI users, since music contains significant spectral energy outside the range of speech (Roy et al., 2012a, 2012b). As a result of these technological constraints, the pitch relationships for music are distorted very early on in the acoustic-electric conversion of sound, even before the electrode-auditory nerve interface.

When current is transmitted to the auditory nerve, the electric fields delivered by an electrode are imprecise and stimulate a relatively large population of nerve fibers for any given frequency (Firszt et al., 2007; Snel-Bongers et al., 2012). Thus, the imprecise pattern of auditory nerve stimulation in itself represents another significant form of degradation for pitch perception. Surgical and anatomical factors (such as geometric arrangement of electrodes, proximity of the array to nerve fibers, and individual cochlear anatomy) also affect the specificity of neuronal subpopulation activation in potentially crucial ways (Cosetti and Waltzman, 2012). Less-than-ideal electrode array placement and/or cochlear abnormalities may lead to increased current stimulation level requirements, further reducing the spatial selectivity of auditory nerve fiber activation for a given frequency.

Most implanted arrays also do not reach the most apical turns of the cochlea—where low frequencies are tonotopically represented—thus preventing full utilization of the normal cochlear frequency response. Currently, no array on the market can be inserted farther than 30 mm from the round widow (where typically cochlea lengths average 33 mm)(Wright et al., 1987), and typical insertion depths average around 20 mm, depending on the array (Ketten et al., 1998). For these more shallow insertions, the characteristic frequencies of the cochlea where the most apical electrode reaches can range from ~300H Hz to over 2000 Hz (as estimated from Greenwood's function) (Ketten et al., 1998). As a result, apical cochlear regions that normally provide important low frequency cues are not stimulated. Many factors such as, electrode array stiffness (stiffer arrays reduce flexibility around apical turns), cochlear abnormalities (especially ossification and malformations), and the experience of the surgeon, can all contribute to limited stimulation of apical cochlear regions (Cosetti and Waltzman, 2012). Patients with deeper insertions demonstrate stronger speech scores (Hochmair et al., 2003; Yukawa et al., 2004). However, in some cases insertions past 400° (measured from the round window) can also result in cochlear damage from the electrode array, which is not ideal for patients who hope to utilize any residual low frequency hearing (Adunka and Kiefer, 2006; Zeng et al., 2008). Techniques

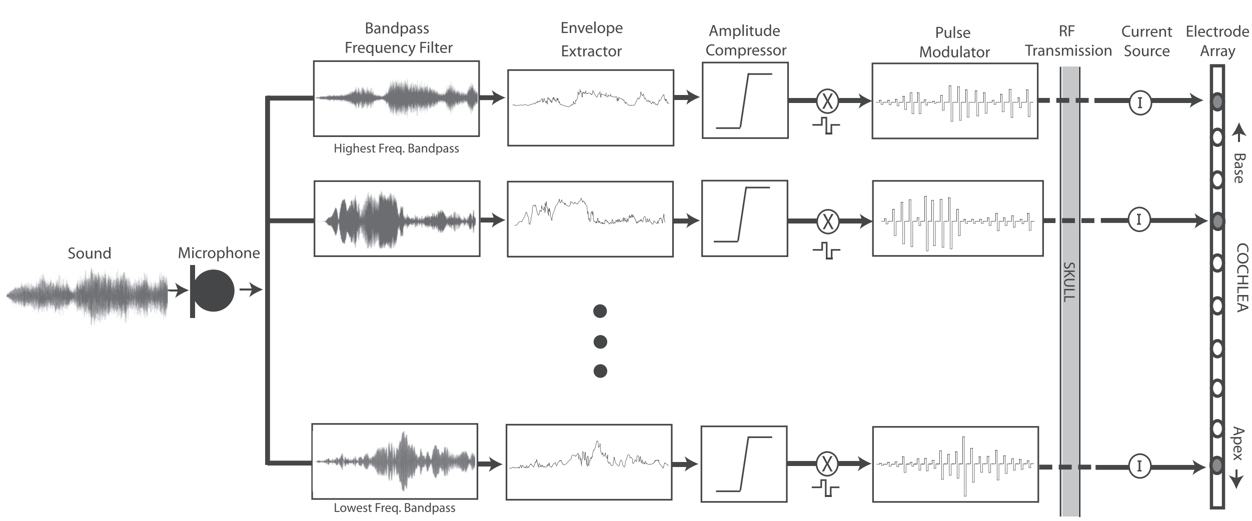

Fig. 1. Schematic of how the multichannel cochlear implant encodes sound. The microphone receives incoming sounds waves. Then, the envelopes of the bandpass filter outputs are extracted and compressed. The biphasic current pulse trains are amplitude modulated by these envelopes. The electrodes within the array stimulate auditory nerve fibers.