Hearing Research xxx (2017) 1–10

Contents lists available at ScienceDirect

Hearing Research

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

Research Paper

Spectro-temporal cues enhance modulation sensitivity in cochlear implant users

Yi Zheng [a,1], Monty Escabí [b], Ruth Y. Litovsky [a,*]

[a] *Waisman Center, University of Wisconsin Madison, 1500 Highland Avenue, Madison, WI, 53705, USA*

[b] *Biomedical Engineering, Electrical and Computer Engineering, University of Connecticut, 371 Fairfield Rd., U1157, Storrs, CT, 06269, USA*

ARTICLE INFO

Article history:
Received 11 March 2017
Received in revised form
12 May 2017
Accepted 23 May 2017
Available online xxx

Keywords:
Cochlear implant
Spectro-temporal
Psychoacoustics
Auditory modulation detection

ABSTRACT

Although speech understanding is highly variable amongst cochlear implants (CIs) subjects, the remarkably high speech recognition performance of many CI users is unexpected and not well understood. Numerous factors, including neural health and degradation of the spectral information in the speech signal of CIs, likely contribute to speech understanding. We studied the ability to use spectro-temporal modulations, which may be critical for speech understanding and discrimination, and hypothesize that CI users adopt a different perceptual strategy than normal-hearing (NH) individuals, whereby they rely more heavily on joint spectro-temporal cues to enhance detection of auditory cues. Modulation detection sensitivity was studied in CI users and NH subjects using broadband “ripple” stimuli that were modulated spectrally, temporally, or jointly, i.e., spectro-temporally. The spectro-temporal modulation transfer functions of CI users and NH subjects was decomposed into spectral and temporal dimensions and compared to those subjects' spectral-only and temporal-only modulation transfer functions. In CI users, the joint spectro-temporal sensitivity was better than that predicted by spectral-only and temporal-only sensitivity, indicating a heightened spectro-temporal sensitivity. Such an enhancement through the combined integration of spectral and temporal cues was not observed in NH subjects. The unique use of spectro-temporal cues by CI patients can yield benefits for use of cues that are important for speech understanding. This finding has implications for developing sound processing strategies that may rely on joint spectro-temporal modulations to improve speech comprehension of CI users, and the findings of this study may be valuable for developing clinical assessment tools to optimize CI processor performance.

1. Introduction

Humans communicate using sounds that are modulated in amplitude, across both frequency and time. These modulations are not mutually exclusive. Human speech is characterized by a complex and continuous pattern of jointly varying spectral and temporal modulations. Temporal modulation patterns carry important syllable boundary information, and spectral modulation patterns carry formant and pitch information; joint spectro-temporal patterns carry information about formant transitions (Liberman, 1996). The rates of temporal amplitude modulations in speech range from those found in syllables (2–5 Hz) and phonemes (15–30 Hz) to those of vocal fold oscillations (>100 Hz) (Rosen, 1992). Spectral modulation rates critical for vowel identification and speech comprehension range from1-4 cycles/kHz (for a center frequency of 500 Hz, 4 cycles/kHz = 2 cycles/octave) (Liu and Eddins, 2008), and rates for vocal gender identification occur at 3–7 cycles/kHz (Elliott and Theunissen, 2009). In normal hearing (NH) subjects, accurate perception of spectral, temporal and spectro-temporal modulations facilitates success on basic auditory tasks such as sound recognition and speech intelligibility (Bregman, 1990; Shannon et al., 1995; Elhilali et al., 2003; Woolley et al., 2005). Further, accurate speech perception depends on the integrity of neural mechanisms in the auditory periphery and central system. Sounds are filtered into frequency-specific “channels” by the auditory periphery, i.e., the cochlea and auditory nerve. In the central auditory system, areas including the auditory midbrain and cortex selectively respond to spectro-temporal auditory cues (Kowalski et al., 1996; Theunissen

* Corresponding author.
E-mail address: Litovsky@waisman.wisc.edu (R.Y. Litovsky).
[1] Currently at: Beijing Advanced Innovation Center for Future Education, Beijing Normal University, Beijing, 100875, China.

http://dx.doi.org/10.1016/j.heares.2017.05.009
0378-5955/

Please cite this article in press as: Zheng, Y., et al., Spectro-temporal cues enhance modulation sensitivity in cochlear implant users, Hearing Research (2017), http://dx.doi.org/10.1016/j.heares.2017.05.009

et al., 2000; Escabí et al., 2003). Maintaining an intact peripheral representation is essential for forward-transfer of information to central auditory centers, which are ultimately responsible for speech perception.

An increasing number of patients with sensorineural deafness receive cochlear implants (CIs) with the purpose of improving everyday communication, which relies on accurate speech intelligibility. The CI is aimed at replacing the function of the cochlea, bypassing damaged sensory hair cells and electrically stimulating the auditory nerve (Wouters et al., 2015). CI users do show some sensitivity to spectral and temporal cues, thus gaining access to at least some aspects of the speech signal. However, variability amongst CI users in speech understanding is very high, such that some patients perform significantly worse than NH subjects while others exhibit near-normal speech comprehension (Peterson et al., 2010; Holden et al., 2013).

The highly variable performance may partly arise from adoption of different strategies for extracting temporal and spectral cue information. The way frequency and timing cues are perceptually integrated can be evaluated by measuring sensitivity to changes in combined spectro-temporal cues. Although spectro-temporal sensitivity, as it pertains to speech intelligibility, has been studied in NH subjects (Chi et al., 1999), spectro-temporal sensitivity in CI users remains unexplored. We hypothesize and demonstrate that, unlike NH subjects, CI users adopt a novel perceptual strategy in which they have heightened detection sensitivity to spectro-temporal modulations. Such an enhancement in the spectro-temporal modulation sensitivity could facilitate extraction and detection of auditory cues in spoken language through the degraded electrical stimulation that CIs provide.

2. Materials and methods

2.1. Subjects

Nine bilateral CI users (9 females) with Nucleus devices participated in the study (Table 1). Nine normal hearing subjects (4 males and 5 females), ranging in age from 20 to 34 years were tested in this study. All subjects had pure tone thresholds at or below 20 dB HL octave interval frequencies between 250 and 8000 Hz. Also, for each subject, the thresholds between the two ears differed by less than 15 dB at any tested frequency. They consented to participation in the study and were paid an hourly wage. This study was approved by the Health Sciences Institutional Review Board of the University of Wisconsin-Madison.

2.2. Stimulus

Fig. 1A illustrates a schematic of the auditory stimuli used in this study. The schematic represents spectrograms of spectral, temporal, and spectro-temporal modulated “moving ripple” sounds. Each moving ripple sound has specific modulation values for the spectral and temporal domains. For spectral-modulation-only sounds, the spectral ripples are static over time (Fig. 1A right column; vertical spacing of bars) while for temporal-modulation-only sounds, the ripples fluctuate dynamically overtime, but the modulations are synchronous across frequency channels (Fig. 1A, top row; horizontal spacing of bars). For joint spectro-temporal modulations, the spectral ripples fluctuate over time asynchronously across frequency channels, generating “moving ripples” where the spectral peaks shift in frequency over time (Fig. 1A). Thus, spectral-modulation-only and temporal-modulation-only sounds comprise one-dimensional modulated functions, whereas spectro-temporal

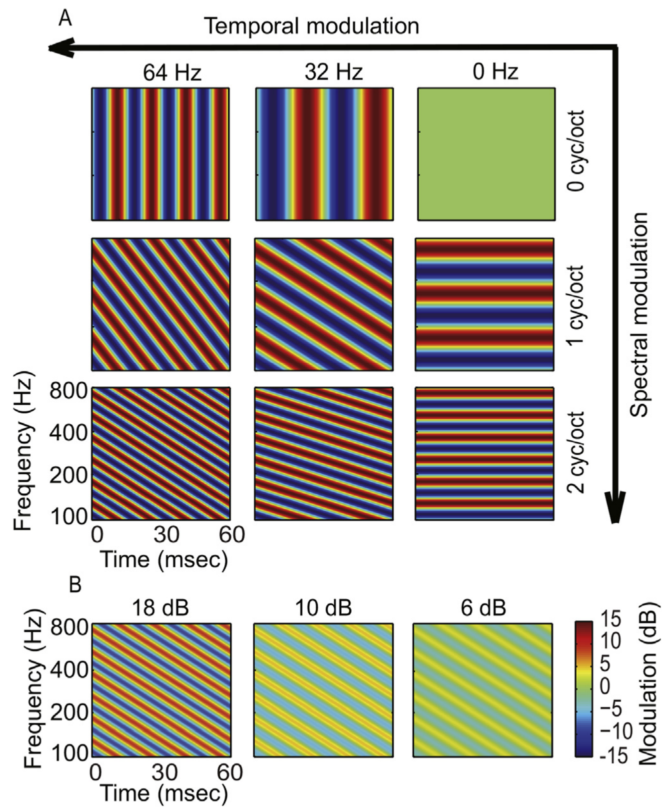

Fig. 1. Experimental stimuli. (A) Schematic diagram of spectro-temporal modulation envelope profiles. Each plot depicts the spectro-temporal modulation to which a particular spectral modulation frequency and temporal modulation frequency is tuned. The stimulus envelopes are modulated to spectral-only (vertical spacing of bars, right column), temporal-only (horizontal spacing of bars, top row), or spectro-temporal modulation (tilted spacing bars). The top-right plot represents the unmoduated signal. (B) Spectro-temporal modulation envelope with different peak-to-valley modulation contrasts. From left-to-right, the decreasing modulation contrast is demonstrated by the color contrast which transitions from sharp (red-to-blue) to shallow (yellow-to-cyan).

Table 1
Clinical etiology.

Subject	Age	Years CI Experience	Ear Tested	Internal Device	Processor
IAJ	57	15	R	CI24R	ESPrit 3G
IBO	48	5	R	Freedom Contour Advance	Freedom
IBP	62	8	R	CI24M	Freedom
IBQ	80	10	R	CI24R	Freedom
IBY	49	5	R	CI512	CP810
IBZ	45	6	R	Freedom Contour Advance	Freedom
ICA	53	11	R	CI24R	CP810
ICB	51	11	R	CI24R	CP810
ICF	71	3	L	CI512	CP810

Please cite this article in press as: Zheng, Y., et al., Spectro-temporal cues enhance modulation sensitivity in cochlear implant users, Hearing Research (2017), http://dx.doi.org/10.1016/j.heares.2017.05.009