Hope for better hearing?

Engineering approaches to studying and treating hearing loss

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Motivation

- At least one in ten Canadians suffers from some degree of hearing loss
  - this number appears to be rising!

- Hearing aids often produce sounds that, while audible, are garbled or muffled and speech understanding is not fully restored

- Some individuals with hearing loss develop tinnitus, a phantom perception of sound
Research questions to answer

- How do we hear, i.e., how do the ear and brain process sounds?
- What is going wrong in individuals with hearing loss and/or tinnitus?
- How can we rectify or compensate for this hearing loss?
- How can we reduce or totally remove the percept of tinnitus?
The human ear

Conductive

Sensorineural

OUTER  MIDDLE  INNER

Brodal, 1946
The cochlea (inner ear)
Cochlear frequency tuning
Neural coding of sounds

- "Place coding" — which neurons are firing and how strongly

- "Temporal coding" — when are neurons firing
How do we hear in noisy environments?

- Pitch, loudness and timing cues

- Directional cues:
  - interaural loudness
  - interaural timing
  - filtering by the outer ear
Interaural Level Differences
Interaural Timing Differences
Sensorineural hearing loss

Main pathologies:

- **Acoustic trauma**
  - sound induced hearing loss

- **Presbycusis**
  - age-related hearing loss
  (progressive acoustic trauma and/or a “dead battery” in the cochlea?)
The organ of Corti

(Smith, 1980)
Normal hair cells
Hair-cell damage
Effects of acoustic trauma

(Liberman and Dodds, 1984)
Presbycusis: a “dead battery”?
Filtering of sound by the inner ear
Conventional hearing aids

- Amplify quiet sounds to make them audible
- Turn down the amplification for loud sounds so they are not too loud (*compression*)
- Cannot compensate for reduced frequency resolution and distorted timing in the impaired ear
Loss of independent frequency channels in the impaired ear

Normal Ear

Conventional Hearing Aid

Normal Auditory Covariance Matrix

NALRP Covariance Matrix for Presbyacusis

(Bondy et al., CAA 2004)
Normal versus impaired onsets

Normal Auditory Onset Representation

Impaired Auditory Onset Representation

(Bondy et al., CAA 2004)
State-of-the-art hearing aids

Incorporate:

- Noise reduction
- Directionality
- Automatic gain/loudness control
- Automated program switching
- Dynamic compression
- Spectral/temporal enhancement
- Feedback cancellation

Attempt to replace:

- Normal brain function
- Normal cochlear function
Noise reduction/directionality

(Dong et al., IHCON 2004)
Pitch and timing cues

(Dong et al., IHCON 2004)
Directional cues: one competing speaker

(Dong et al., IHCON 2004)
Directional cues: many competing speakers

(Dong et al., IHCON 2004)
A new approach: including the ear in the design procedure
A computational model of the normal and impaired ears

(Bruce et al., JASA 2003)
Trainable hearing aid amplification algorithm

$E$ = signal - trainable hearing aid (Becker et al., NICE 2002)
Restoring more independent frequency channels

Normal Ear  Conventional Hearing Aid  Trained Hearing Aid

Normal Auditory Covariance Matrix  NALRP Covariance Matrix for Presbyacusis  Covariance Matrix for Presbycusis after Information Shaping

(Bondy et al., CAA 2004)
What is tinnitus?

- The experience of noises in the head and/or ears, when no corresponding external sound is present.

- The perceived sounds are highly varied amongst individuals. The most common are ringing or hissing sounds.
What causes tinnitus?

- The most common cause of tinnitus is hearing loss due to acoustic trauma or aging.

- Other less common causes include drugs, stress, hearing diseases, head and neck injuries, non-auditory neural input.
Measurement of tinnitus

(Eggermont and Roberts, TINS 2004)
Where is that sound coming from?

- In the vast majority of cases, the abnormal neural activity that is perceived as tinnitus **does not** originate in the ear.

- Most forms of tinnitus are due to abnormal brain activity, but the exact locations and causes are still to be determined.
Possible sources of tinnitus

- Cortex
- Midbrain
- Brainstem
A behavioural test for tinnitus in animals

(Kaltenbach et al., Neurosci. Lett. 2004)
Abnormal brainstem activity in animals with tinnitus

(Kaltenbach et al., Neurosci. Lett. 2004)
Modelling abnormal midbrain activity

(Ko, M.A.Sc. Thesis 2004)
Cortical reorganization

(Eggermont and Roberts, TINS 2004)
Modelling cortical changes

Predicts:

- Reorganization
- Higher spontaneous activity
- Abnormal synchrony between neurons

(Dominguez et al., submitted 2004)
Why can tinnitus be so distracting and/or annoying?
Current treatments for tinnitus

- Sound therapies:
  - masking
  - auditory re-training
- Counselling, relaxation techniques, etc.
- Medication: tranquilizers, anti-depressants, etc.
- Hearing aids
Future treatments for tinnitus?

- Sound therapies to reverse neural reorganization
- Drugs or gene-therapy to reverse hearing loss and reverse neural reorganization
- Improved hearing aids
Electrical stimulation of the auditory nerve: a treatment for deafness

1790s - Volta inserts metal rods attached to a battery into his ears ⇒ “noise like the boiling of thick soup”

1930s - Teams from the United States and the Soviet Union achieve hearing sensations in deaf individuals with electrical stimulation to the middle ear

‘50s - French team implant first successful intracochlear electrode ⇒ perception of prosody and aid to lip-reading

‘60s-‘70s - Development of single-channel implants as experimental devices

‘70s - Drs. William House, Blair Simmons and Robin Michelson implant the first wearable single-channel implants designed for long-term stimulation.

1978 - Prof. Graeme Clark and the University of Melbourne team implant first multi-channel implant

‘80s - Nucleus (now Cochlear Corp.) develops commercial device approved by FDA
How a cochlear implant works
Short-electrode arrays

(Gantz and Turner, 2003)
Regeneration of hair cells?

- Some species can regenerate hair cells
- Can this be done in humans too?
Reconnection of auditory nerve fibers to hair cells?
Summary

- The last century showed great advancement in microelectronics, signal processing, computer modelling and medical science.

- Biomedical engineering offers exciting prospects for combining these fields to design new treatments for hearing loss and tinnitus in this new century.
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