Ear Physiology

Notes on Speech and Audio Processing

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Introduction

- Human auditory system is capable of
  - distinguish subtle difference in frequency and intensity of sounds.
  - making sense of noisy sounds.
  - discerning mixed sounds from different sources.
  - “sounds who’s speaking!”
- Helmholtz proposed that the auditory nerve processes sound *tonotopically*, meaning different nerve bundles are sensitive to different frequencies.
- In this view, the auditory system is seen as a (sophisticated) filter bank.

The Peripheral Auditory System

- There are three components: the outer, middle and inner ears.
- The input to this system is an acoustic signal and the output is a collection of neural spikes into the brain.
- The physiological process

air pressure change $\longrightarrow$ vibration of ear drum

$\longrightarrow$ malleus $\longrightarrow$ incus $\longrightarrow$ stapes (middle ear)

$\longrightarrow$ oval window $\longrightarrow$ fluid $\longrightarrow$ basilar membrane (cochlea)

$\longrightarrow$ hair cells $\longrightarrow$ neural spikes

Cochlea

- Refer to Figure 14.3. The shape of cochlea resembles a snail. It is “unwinded” in Figure 14.4. The end points are called the **base** and the **apex**.
- The basilar membrane is relatively narrow and stiff near the base; it is wider and less stiff near the apex. As a result, high frequencies excite basal portion and die out further down, while low frequencies reach peaks near the apex.
- This mechanism supports the idea of filter bank. This is illustrated in Figure 14.5.

Auditory Nerves

- The motion of basilar membrane causes stereocilia motion, which in turn leads to neural spiking of auditory nerves.
- Refer to Figures 14.6 - 14.8 for further information on auditory nerves.
- Physiological measurements have uncovered some general properties of auditory nerves, including adaptation, tuning, synchrony, and non-linearity.

Adaptation

- When a stimulus is firstly applied, the spike firing rate of an auditory nerve rapidly increases. If the stimulus remains, the rate decreases in an exponential manner to a steady-state value.
- After the stimulus is removed, the firing rate decreases rapidly below the spontaneous rate before resuming this rate.
- Figure 14.9 illustrates this point.

Tuning

- Basilar membrane (BM) acts like a bank of tuned filters. Furthermore, the tuning frequency is a function of the position on BM.
- As a result, the auditory nerve has a similar tuning property. That is, different nerves are tuned to different frequencies.
- Figure 14.10 shows the sound pressure level that is required to increase the firing rate by a constant for 6 different nerve fibers. Here each curve represents an auditory nerve and one can see the dependence on frequency of the firing rate.

Synchrony

- Apply a tone and measure the histogram of time intervals between adjacent spikes of auditory nerve.
- The time between peaks (of histogram) is the inverse of the frequency, indicating that the spikes tend to occur in synchrony (a.k.a. phase locking) with the applied stimulus.
- It has been found that phase locking does not occur above 5 kHz, for cats.

Non-linearity

- Saturation: the rate of spikes that a nerve fiber can generate is limited biologically. Note this saturation rate depends on the fiber.
- Two-tone suppression: the application of another tone reduces the steady state firing rate of nerve caused by an original tone.
- Masking by noise: The response of a fiber to a tone is suppressed by an accompanying noise.
- Combination tones: If a fiber is excited by two tones, a combination tone not present in the stimulus may appear.

Summary

- The outer ear terminates at the eardrum. It is basically an acoustic tube.
- The middle ear transmits mechanical energy from malleus (driven by the eardrum) to stapes (driving the inner ear fluid).
- The inner ear contains fluid, basilar membrane and hair cells.
- The BM motion is transmitted to the hair cells, causing auditory nerves to fire neurons.
- Auditory nerves manifest adaptation, tuning, synchrony, and non-linearities such as saturation, masking and suppression.