DAT335 – Music Perception and Cognition
Cogswell Polytechnical College
Spring 2009

Week 4 – Class Notes

The Perception of Loudness (cont...)

The Detection of Intensity Changes and the Coding of Loudness

The smallest detectable change in intensity of a stimulus can be measured by using a two-alternative forced-choice (2AFC) procedure, in which successive and differing stimuli are presented. The three main intensity discrimination measurement methods are:

1. *Modulation detection-* in one interval the stimulus is unmodulated and in the other it is amplitude modulated at a slow regular rate. The subject indicates which interval contains the modulation.
2. *Increment detection-* a continuous background stimulus is presented and an increment in level is imposed on the background in one of two possible intervals, indicated by lights. The subject indicates which interval contains the increment.
3. *Intensity discrimination of gated or pulse stimuli-* two separate pulses of sound are presented successively, one being more intense than the other. The subject indicates which is more intense.

While experimental results may vary depending on the method used, their overall trend is similar. Thresholds for detecting intensity changes are often specified in dB, as the change in level at threshold, ΔL.

For example, in the third method, if one sound has intensity I, and the other sound has intensity $I + \Delta I$, then the value of ΔL is given by

$$\Delta L = 10\ log_{10}\{\ (I + \Delta I)/I\ \} \text{ or as } 10\ log_{10}(\Delta I/I)$$

The smallest detectable intensity change, for wideband noise or bandpass-filtered noise, is approximately a constant fraction of the intensity of the stimulus. Meaning that $\Delta I/I$ is more or less constant. This can be considered an example of Weber's law, which states that the smallest detectable change in a stimulus is proportional to the magnitude of that stimulus. In this case, $\Delta I/I$ is called the Weber fraction. If the smallest detectable change is expressed in dB as well, then ΔL too is constant regardless of the absolute level. This holds true for sounds 20dB above threshold to 100dB above threshold.

However, for pure tones, Weber's law does not hold. Discrimination increases at higher levels, as measured by the Weber fraction (it increases at sound levels above 100dB). This has been called the “near miss” to Weber's law.

The implications of these findings in psychological intensity coding in the auditory system are: 1) the auditory system is capable if detecting changes in level for a range of levels, or dynamic range, of at least 120dB; 2) Weber's law holds for the discrimination of burst noise; and 3) discrimination of the level of pure tones improves with increasing sound level up to 100dB SPL.

The Dynamic Range of the Auditory System

The wide dynamic range of the auditory system has been considered difficult to explain int terms of neural activity. Several studies of nerve fibers have shown that for those fibers with wide dynamic ranges of 60 dB or more exist in a relatively small proportion (~10%). Also, when those fibers where stimulated with a tone close to the CF at sound levels above 60 dB SPL, all neurons showed a substantial reduction in the slope of the rate versus intensity function. Thus, changes in intensity only resulted in small changes in neural firing rate. However, if intensity discrimination were based on changes of the firing rate of neuron with CF's close to the stimulus frequency, it might me expected that intensity discrimination will become worse at sound levels above 60 dB SPL. In reality, this is not the case.

It has been suggested that another mechanism for coding intensity changes at high intensities exists. One explanation relies on the way in which the excitation pattern of the stimulus would spread with increasing intensity. At high intensities, the majority of neurons at the center of the pattern would be saturated, but changes in intensity could be signaled by changes in the firing rates of neurons at the edges of the pattern. It might seen like a contraindication for the discrimination of wideband stimuli, like white noise. An excitation pattern created by white noise theoretically has no edges, so all the neurons are saturated by a high intensity stimulus. However, because human hearing is not equally sensitive to all frequencies, as indicated by absolute threshold curves and equal-loudness contours, the nerve fibers near the midrange CF's would be indeed saturated and those located at very low or high CF's would not. Further studies have indicated that the spread of excitation is not essential for maintaining the wide dynamic range of the auditory system. As a result, yet another mechanism for intensity discrimination is needed.

The timing of neural impulses has been thought to provide a cue to the intensity of a tone in a noise background. When a tone, above threshold, is presented against a noise background, some neurons phase lock to the tone, while the ones with CF's far apart from that of the tone are driven by the noise and have a more random firing pattern. If the tone is increased in intensity, more neurons will become phase locked to it and those already locked will increase their temporal regularity. In other words, a change in temporal regularity of the neural firing patterns could indeed signal the intensity change of a tone. A mechanism of this nature could operate over a wide range of intensities and would not be affected by saturation effects, because a change in temporal patterns of firing can occur for saturated neurons. However, this mechanism would be limited to frequencies below 4-5 kHz.

In general, any change in the spectral composition of a complex sound results in a change in the phase locking pattern as a function of the CF.

More recently, the wide dynamic range “problem” has changed in focus. Studies have observed how a single neuron has the capacity to carry information about intensity changes. This capacity depends on both the shape of the rate versus the level function and the statistical properties of the neural responses, particularly their variability at each level. For example, is the variability in firing rate is very low, even a small change in the mean firing rate in response to a change in intensity will be sufficient to “code” the intensity change. The threshold if large at high levels because stimuli close to or below the absolute threshold of the neuron result in minimal changes in firing rate. At intermediate levels, the threshold change ΔL can be as low as 2-3 dB.

These type of studies indicate that the performance of human intensity discrimination tasks can be accounted for if it is assumed that the information is combined optimally from a relatively small number of single neurons. The number of neurons required is approximately 100. Thus, if we take in account that all of the information contained in the firing rates of all 30,000 neurons in the auditory nerve were used, then the intensity discrimination would be much better than it really is. For example, the ΔL would be less than 0.1 dB for 1000 Hz tone bursts at medium intensity levels.

It appears that intensity discrimination is limited by the capacity of more central parts of the auditory system to make use of the information in the auditory nerve. In other words, if the information in the auditory nerve is impoverished, the intensity discrimination will be impaired.

Weber's Law

Threshold measurements from single neurons do not conform to Weber's law. This law can only be predicted by models which combine the firing information from a relatively small number of neurons (about 100) whose thresholds and dynamic ranges are appropriately staggered so as to cover the entire dynamic range of the auditory system. Such models assume that the information from the neurons with similar CF's is combined, and that there are many independent “channels” responding to a limited range of CF's. Weber's law is assumed to hold for each channel, such that the information about the levels of components in complex sounds can be coded over a wide range of overall sound levels. However, recent studies show that each frequency channel does not conform to Weber's law.

The Near Miss to Weber's Law

Two factors are thought to be responsible for the intensity deviation from Weber's law. The first considers the nonlinear change in excitation patterns with level changes. Meaning that with increasing intensity levels, the excitation pattern grows in a compressive manner closer to its center, but more linear in the high-frequency side. The end result being a rate of growth of response with increasing input level is greater on the high-frequency side of the excitation than around its center.

The second factor suggests that subjects do not make use of the information from only a single channel (auditory filter output). Rather, they combine information from all of the excited channels (across the entire excitation pattern). An increase in tone intensity will increase the number of active channels, thus resulting in an improved performance.

Loudness Adaptation, Fatigue, and Damage Risk

All sensory systems that are exposed to stimulus of sufficient duration and intensity produce change in responsiveness. Some changes occur during the presentation of the stimulus, so that its apparent magnitude decreases, or its disappears completely. Other changes are apparent after the end of the stimulus.

Auditory fatigue results from the application of a stimulus which is usually considerably in excess of that required to sustain the normal physiological response of the receptor, and it is measured after the stimulus has been removed.

Auditory adaptation is the process of equilibrium. The response of the receptor to a steady stimulus declines as a function of time until it reaches a steady value at which the energy expended by the receptor is just balanced by the metabolic energy available to sustain it.

Post-Stimulatory Auditory Fatigue

The common index of auditory fatigue is the temporary threshold shift (TTS). The five major factors influencing TTS are:

1. The intensity of the fatiguing stimulus (*I*).
2. The duration of the fatiguing stimulus (*D*).
3. The frequency of the fatiguing (exposure) stimulus (F_e).
4. The frequency of the test stimulus (F_t).
5. The time between cessation of the fatiguing stimulus and the post-exposure threshold determination, or recovery interval (*RI*).

TTS generally increases with *I*, and for low intensities TTS changes relatively slowly. TTS occurs only for test tones with frequencies F_t close to F_e, and as TTS and *I* increases, so does the frequency range over which the effects occur increase. For intensities of 90-100 dB, TTS rises abruptly, and has been suggested that this indicates a change from fatigue of a transient nature to a fatigue that is more permanent and pathological in nature.

Fatigue also increases with *D* and its effects are more marked at high frequencies. TTS decreases with increasing *RI*, and has a recovery ("bounce") following the exposure.

Auditory Adaptation

Studies in auditory adaptation make use of loudness balance test, one of the known as simultaneous dichotic loudness balance (SDLB). For example, if a tone of fixed level, say 80 dB SPL, is applied to one ear (test ear), and a loudness balance is made with a comparison tone of the same frequency but variable level applied to the other ear (control ear). The balance, for a normal subject, is obtained with a level of about 80 dB SPL. The tone in the control ear is now removed, but that in the test ear is continued for a further 3min. Following this adaptation period, a loudness balance is established once again. It is generally found that the tone in the control ear now produces a loudness match at a lower level, say 60 dB SPL. Thus, the amount of adaptation corresponds to a change in level of 20 dB.

Abnormalities of Loudness Perception in Impaired Hearing

Loudness Recruitment

This cochlear defect refers to an unusually rapid growth of loudness level as the sensation level of a tone is increased. For example, consider a person has a hearing loss at 4000 Hz of 60 dB in one ear only. If a 4000 Hz tone is introduced into his or her normal ear at 100 dB SPL, then the tone which sounds equally loud in the impaired ear will also have a level of about 100 dB SPL. The ear with ear recruitment seems to "catch up" with the normal ear in loudness. Although loudness recruitment is considered pathological, a similar phenomenon occurs in normal hearing listeners.

This phenomenon can be accounted for the fact that a person may not be able to hear faint sounds, but sounds of high intensity are just as loud as for a normal listener. Sounds which are easily audible may not be easily intelligible.

Loudness recruitment consistently occurs in cochlear disorders and is usually absent in conductive deafness and in retrocochlear deafness. It is probably connected with hair cell damage, in particular outer hair cells. There have been reports of recruitment caused by brainstem disorders.

An explanation for loudness recruitment is that it results from damage or loss of the active process in the cochlea that enhances sensitivity for low input sound levels. This active process is nonlinear, and results in an amplification of the BM response to low-level sounds, while leaving the response to high-level sounds relatively unamplified. A damaged process will not produce an amplified response to low-level sounds, but the absolute threshold is elevated. However, the response to high-level sounds remains more or less normal.

Pathological Adaptation

Abnormal metabolic process in the cochlea or auditory nerve can result in a very rapid decrease in neural response, although the response to the onset of a sound may be normal or near normal. The perceptual correlate of this is adaptation which is more extreme and more rapid than normal. The pathological condition associated with this phenomenon is a tumor (acoustic neuroma) growing near and pressing on the auditory nerve.