EECS225d Audio Signal Processing in Humans and Machines	**Spring 1995**

Lecture 16: February 24, 1995

Lecturer: Steve Greenberg — *Scribe: Jeff Bilmes*

A Bridge Between Place and Time

16.1 Introduction

This talk will be a journey through conceptual and historical aspects of various place/time perceptual experiments. Although many are now known to be inaccurate or even completely fallacious, all the experiments are, in one way or another, relevant to the issue of the place/time problem. We will conclude with what is believed to be a resolution of the place/time dichotomy by suggesting a model that accounts for the missing fundamental phenomena under a dual place/time paradigm.

So far in this class, we've covered the basic mechanics of the auditory system. Herewith, we will attempt to understand the type of perceptual problems the auditory system is designed to solve. One example is the binding problem, i.e., how do we group together the acoustic patterns of an real-world object into a coherent perceptual source.

We will study the place/time dichotomy[E78] by taking a look at a variety of relevant perceptual experiments and/or observations. The purpose of presenting these particular experiments is that, when considered together, they lead to a unified conceptual framework. In the following, no single experiment shows conclusively that either the place theory or temporal theory is correct. This will lead to our eventual conclusion that, similar to the final conclusion about the particle and wave theories of light, both the tonotopic and temporal properties of the auditory system are key in order to properly understand its workings and to accurately build a model.

16.2 Rough Outline

- The link between perception and physiology
  - the binding problem
  - acoustic object formation and source tracking
  - perceptual invariance, representational stability
- Some history of the place versus time issue
  - Ohm versus Helmholtz versus Seebeck versus Wundt & Rutherford
- Origins of frequency selectivity
  - tonotopic organization
  - the Cochlear traveling wave
  - The ability of the ear to distinguish between different frequencies
- Periodicity Coding and Pitch
  - Temporal Coherence and Coincidence Detection

16.3 Background

We begin with some words of wisdom.

> Some researchers are of the opinion that it is no longer necessary to study the history of science because science has progressed so fast and always linearly, that earlier experiences are of no value. I do not believe this, but believe like many of my ontological colleagues that scientific progress is more like a spiral, as in the cochlea of the ear, which always progresses in one direction but with many ups and downs and with many repetitions of earlier forms.
>
> Georg von Bekesy
> Nobel Laureate for his research on the cochlea

Why study the ear?

> How else can the question as to how a tone is perceived be addressed but through an understanding of the ear?
>
> August Seebeck
> Discovered the "Missing Fundamental" (1844)

16.4 Setting The Stage

The place versus time issue has been a perennial controversy for quite some time. The place argument began with Ohm's acoustic law, Helmholtz's place theory of pitch and timbre, Seebeck's missing fundamental demonstration, and Wundt and Rutherford's telephone theory. Further support for this case was given by von Bekesy's observations that the cochlea vibrates as a traveling wave.

The argument for temporal coding of frequency began with Wever's volley theory and received support by Schouten's model of the residue.

We now describe each of the above in slightly more detail.

16.4.1 History of Place

In the 1840's, Ohm[O43] proposed his acoustic law, which states that the ear does a form of Fourier analysis of sound. He was inspired by the then recent results of Fourier who stated that any waveform can be uniquely represented by an appropriate sum of sinusoids. Ohm reasoned by analogy that the ear must also do some form of encoding of auditory information, although he did not have any direct empirical evidence. This began the more than 100 years of controversy which followed.

In the 1860's, Helmholtz[He63] proposed his place principle of frequency coding (i.e., his resonance theory). He postulated that there exists tuned resonators (See Figure 16.1) in the basilar membrane with a constant relative bandwidth or a constant Q of about 25 (recall that Q = center frequency/bandwidth).

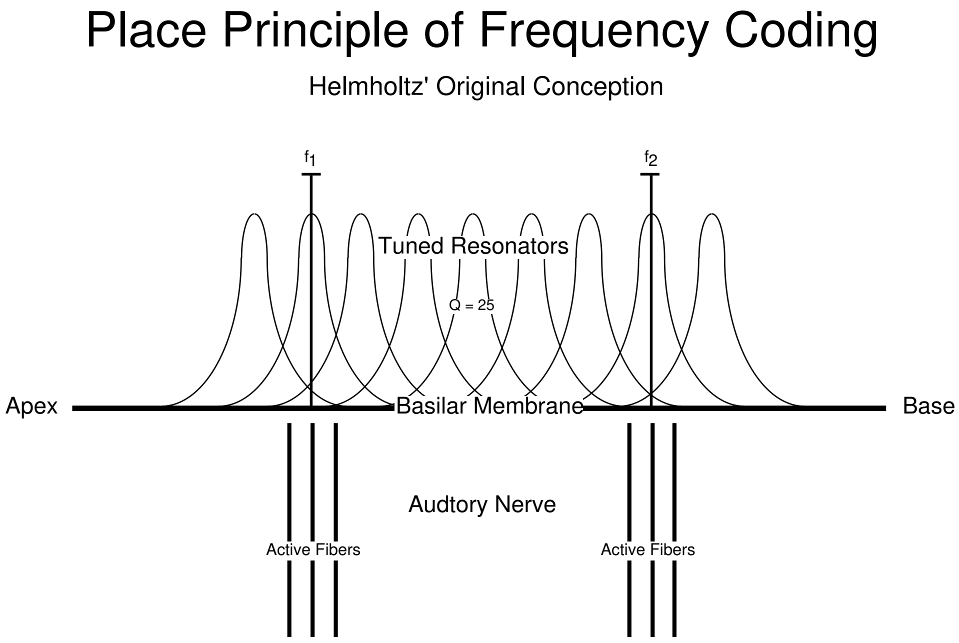

Figure 16.1: Helmholtz's Conception

He postulated that there was about a 4% difference of the resonators in the ear (i.e., if f_i is the center frequency of the i^{th} resonator, then $f_{i+1} = 1.04 \times f_i$). Actually, we now know that this value is about 16%.

Later on, in the 1920's, Georg von Bekesy[B60], who was a pioneer of modern research on the ear, wanted to know how the ear analyzes frequencies in a goal to design a better telephone receiver. He observed the motion of the basilar membrane in the inner ear and proposed that each frequency maximally stimulates hair cells at a particular place along the cochlea. Although similar to Helmholtz in that this is a place theory, the mechanism by which a particular place is simulated is very different than a set of tuned resonators. Bekesy proposed that different places were stimulated because the cochlea vibrates in a traveling wave like motion. The point at the maximum of the envelope of the traveling wave corresponds to the nerve fiber that is maximally stimulated (see Figure 16.2).

16.4.2 A Brief History of Time

Moving back in time, once again, to the 1840's (note, 20 years before Helmholtz) August Seebeck demonstrated the effect of the missing fundamental (in fact, organ builders knew about this effect in the 1500s). Seebeck generated a series of complex harmonic waveforms and removed the lowest frequency, the fundamental. If Helmholtz's theory is right, we would expect that the pitch of such a complex tone should change. But the pitch, as you heard in class, does not change. Seebeck concluded that periodicity is important in a pitch, i.e., that two signals with differing spectra but with the same overall periodicity will have the same pitch.

Note that Helmholtz was actually aware of Seebeck's demonstration, but argued that the missing fundamental was due to a non-linearity in the middle ear which reintroduced the fundamental frequency. Later, Schouten's adjusted fundamental frequency experiment and Licklider's noise masking experiment[Li51,Li62]

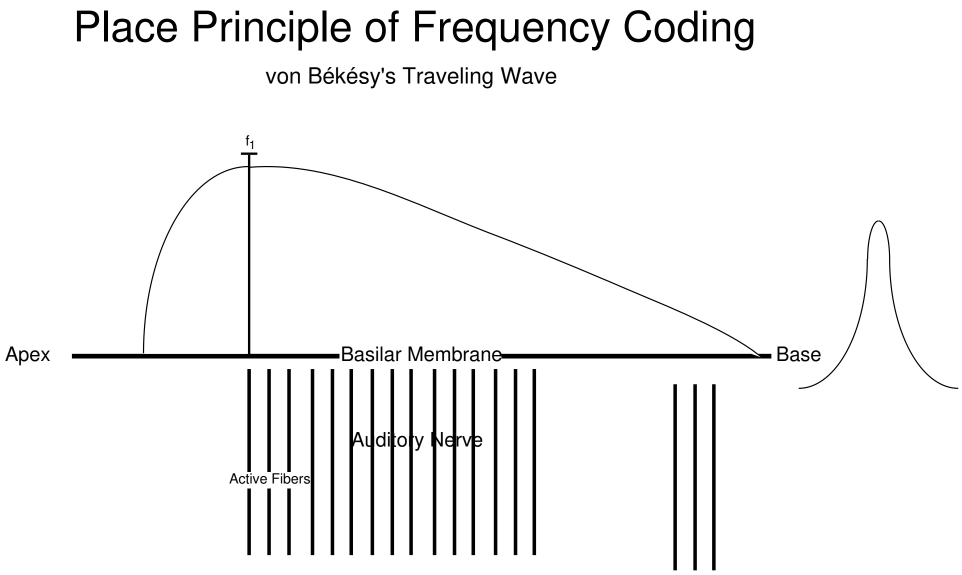

Figure 16.2: von Bekesy's Conception

demonstrated fairly conclusively that such a non-linearity could not account for the pitch of the missing fundamental.

Later in the 19th century, Wundt and Rutherford gave no apparent evidence for but posited the existence of temporal coding of frequency information in the inner ear.

In the 1930s, we begin the modern age of such studies. In particular, the availability of more sophisticated electronics made new experimental techniques possible. Glen Weaver's Volley principle[W49] is particularly important. He recorded the temporal aspects of the electro-potential of animal nerve fibers. From these data, he concluded that the temporal information reflected an accross-channel reconstruction of a signal's periodicity. In other words, the fibers are temporally encoding the frequency information. Weaver also noted that this neural frequency following deteriorates above 4-5 kHz. Interestingly, in experimental results, humans report that pitch of high frequencies is much less distinct than that of signals within the frequency following range.

Recall the neural phase locking[RBAH67] we have heard about in class and that we have seen in interval histograms. Weaver suggested that individual nerve cells phase lock to the stimulus waveform and that the reported electrical potential reflected the integration of large populations of such phase-locked responses. That is, when he looked at an interval histogram of neural firing, he noticed that there is a tendency (i.e., a highest probability) to have high potential at the time of the period peaks for a certain frequency and neural fiber.

One problem, however, was that auditory nerve fibers have a maximum firing rate, and that rate is far less than 5kHz (we now know it to be about 250Hz). Because this *resting* period of a nerve fiber is longer than the shortest period where this effect occurs, Weaver posited the Volley principle. This principle states that several nerve fibers work together as a size n group, with each fiber of a set firing every n^{th} period. Essentially, the fibers of a group perform temporal multiplexing across a frequency channel.

Note, however, that we now know that as we move up the auditory pathways, this temporal coding applies only to progressively lower frequencies. At the auditory cortex, for example, temporal coding does not occur above about 20OHz. Could this be an epiphenomenon of some other representational form? If so, what is it? Where does the temporal information from higher frequencies go? At this point, we don't know.

16.5 The Big Question

The big question at this point is how do we resolve these two perspectives. We've seen evidence that frequency is encoded by place along cochlea, but also evidence that frequency is encoded by timing information (temporal distribution of aural discharge).

Schouten tried to solve this dichotomy in what is now called his residue model[S92]. He argued that the basis of the missing fundamental is the common periodicity of high-frequency, harmonically related components. In particular, the low harmonics are neurally encoded as independent frequency components. The high harmonics, however, are not seen as independent entities as there are interactions. That is, in high frequency neural channels, each channel encodes the combination of multiple harmonics into a waveform that is periodic. So, assuming this is true, we can eliminate lowest frequency harmonics and still observe the periodicity of the resulting signal in the higher combined channels. This, of course, is related to the critical bandwidth.

In fact, in his analysis, Schouten was beginning to address the binding problem. That is, he began to ask how do we associate seemingly independent neural excitations driven by single sources into a perception of an object as a whole (especially under typical adverse acoustic conditions). Schouten's idea was that there exists coherence in the neural excitation pattern; in his case it was the common periodicity.

This leads us into a large set of currently unanswered questions, perhaps appropriately termed *Object-Oriented Hearing.*

16.6 Object-Oriented Hearing

There are many questions that remain unanswered. Most of what we can do at this point is ask them (and ask for funding to answer them).

The binding problem asks the following question: how are neural patterns associated with the same source woven into the same cognitive representational object? What is the neural binding force? Is it common periodicity as Schouten implied? What are the other forces?[1]

How do we create an acoustic image of the external world. That is, we go from neural activity to internal mental representations of objects, forces, etc. In a sense, we "see" the world through our ears. How is this done?

Furthermore, what forces allow us to perceive stability and invariance in our auditory image. That is, under many different and adverse acoustic conditions we still have the perception of the same speaker, the same objects, the same location, etc. Which representational components preserve information across these grossly varying acoustic conditions.

We will argue that these questions lead to a unified Space-Time theory of auditory functioning. In particular, that there is neural coherence in the auditory periphery, and that there are multiple levels (a hierarchy) of correlation in the central pathway. But before we get to that, we present a glossary of key terms.

[1] We will hear more about this later in the semester under the topic: Auditory Scene Analysis[Br90].

16.7 Frequency Selectivity

There is little disagreement that the ability of the auditory system to perform a frequency analysis is crucial to humans' ability to process sound. This idea, and the idea that different frequencies are processed according to spatially different regions of the auditory system, is called tonotopic organization. Note that tonotopic organization occurs at almost all levels of the auditory pathway. The tonotopic organization is stable over a wide range of sound pressure levels, although it begins to break down at high intensity levels (i.e., the response region in the cochlea to a particular frequency widens as the SPL level increases). Note that tonotopic organization of the auditory system has long been considered the primary basis in which frequency is encoded. But it could, in fact, just be the substrate through which it is carried.

What are the origins of this frequency selectivity? That is, why is the ear tuned precisely the way it is? It is hard to answer that question, especially because there are disparities between perceptual and physiological measures of selectivity. We will, however, try to present a theory that helps us answer this question.

Note that the cochlear representation for three significantly different signals can be very similar under the mean-rate/place representation[Bi77]. Consider the 3 signals listed in Figure 16.3, a 70 dB sinusoid, a complex tone, and white noise. All have approximately the same mean firing rate across the characteristic frequencies of different neurons in the auditory pathways.

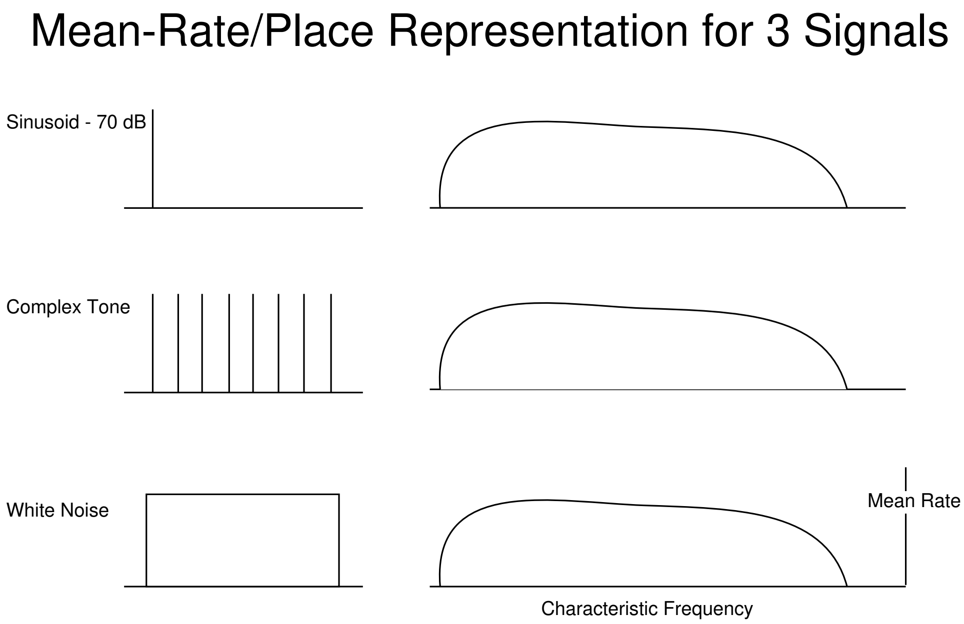

Figure 16.3: Spectral-Temporal Organizations

But we know that different neurons have different characteristic frequencies. That is, a particular fiber has a certain frequency range to which it is most sensitive (i.e., minimum SPL). As the stimulus moves away from that range, the firing rate decreases if we keep the amplitude constant.

Also, the Q's of higher frequency nerve fibers is greater than the Q's of lower frequency nerve fibers. But that doesn't mean that constant Q filter banks are a close approximation. In fact, when we plot Q as a function of characteristic frequency, we see Q increasing approximately linearly with increasing characteristic frequency. I.e., there are a large range of Q's. So, constant Q filter banks are not a good approximation to cochlear processing. A better model, perhaps, would be linearly increasing Q.

There are, in fact, many strange aspects of auditory filtering system. For example, at low SPLs, empirical experiments produce results that agree well with the the rate-place theory of pitch perception. At high SPLs, however, we get a spread of activation across nerves. This raises the issue as to how we perform spectral analysis and thereby perceive pitch at high intensity levels?

16.8 The Critical Band

The results of Harvey Fletcher are particularly relevant here. He performed an experiment where subjects attempted to detect a pure tone in noise. The noise is varying in bandwidth, but the power of the noise is kept constant. When the noise is broadband, the tone detection threshold didn't change as the bandwidth narrows. This means that we essentially do integration over bandwidth in the inner ear. And since it changes little with changing SPL, there must exist a regular gradient. That is, with wide band noise plus a signal, we suppress the discharge rate to spectrally sharpen the spectral representation. This seems to suggest some form of lateral inhibition or other sharpening mechanism. One possible locus for this sharpening is in the cochlear nucleus. What is the origin of this enhanced frequency sharpener? Again, we do not exactly know.

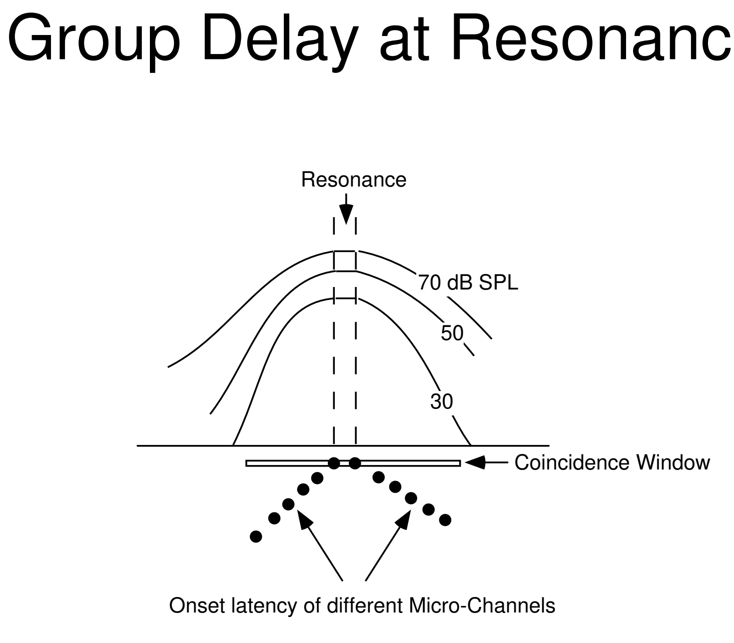

Figure 16.4: Phase Principle

In 1952, Huggins[Hu52] worked on his phase principle (see Figure 16.4). This essentially relates to the sensitivity in the ear to the phase of neural excitation reflecting the traveling wave's transit time. This further suggests that spectral sharpening could be the result of such phase sensitivity. He also showed a resonogram, looking at the phase response both with and without lateral inhibition. From this, he was able to do good formant tracking.

Auditory nerve micro-channels correspond to a way of sensing resonances at specific locations in the coclea. This is accomplished by sensitivity to different delays across frequency channels. Detecting these delays

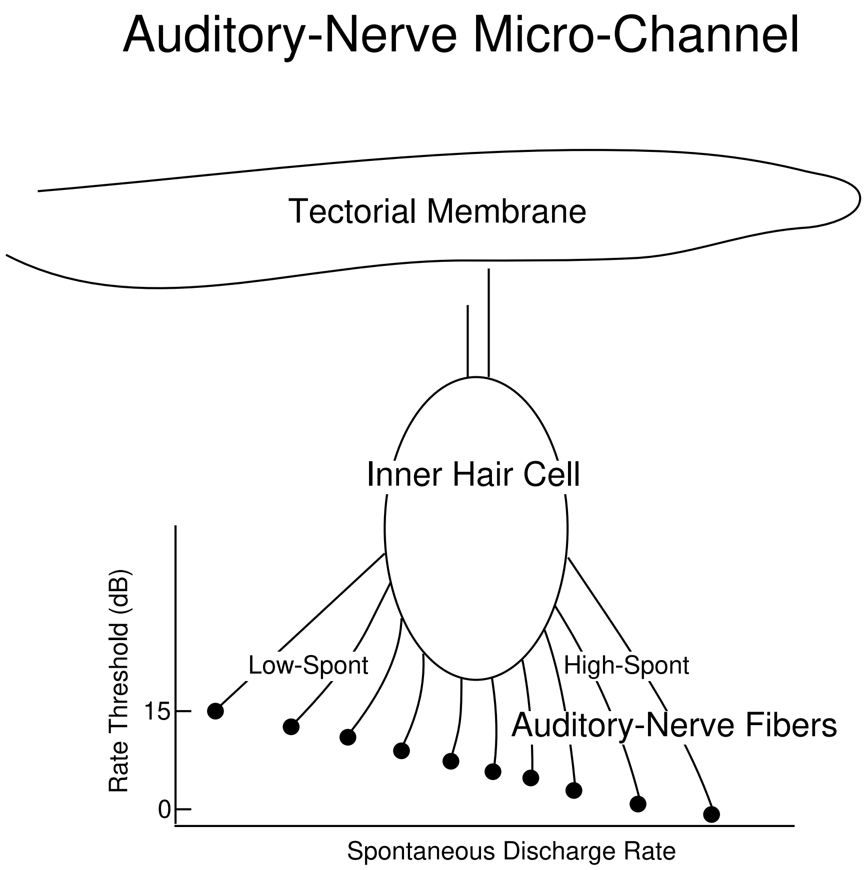

Figure 16.5: Auditory Nerve Micro-Channel

is probably performed by coincidence detector[A82] cells, i.e., neurons that fire in a small time window depending on the temporal difference of the firings of incomming neurons. If the temporal difference is outside a certain time window, then the cell doesn't respond as well as when the inputs are synchronous. Onset shoppers of the postero-ventral cochlear nucleus respond as if they are coincidence detectors.

We'll skip periodicity pitch and onset timing since Ben covered it before.

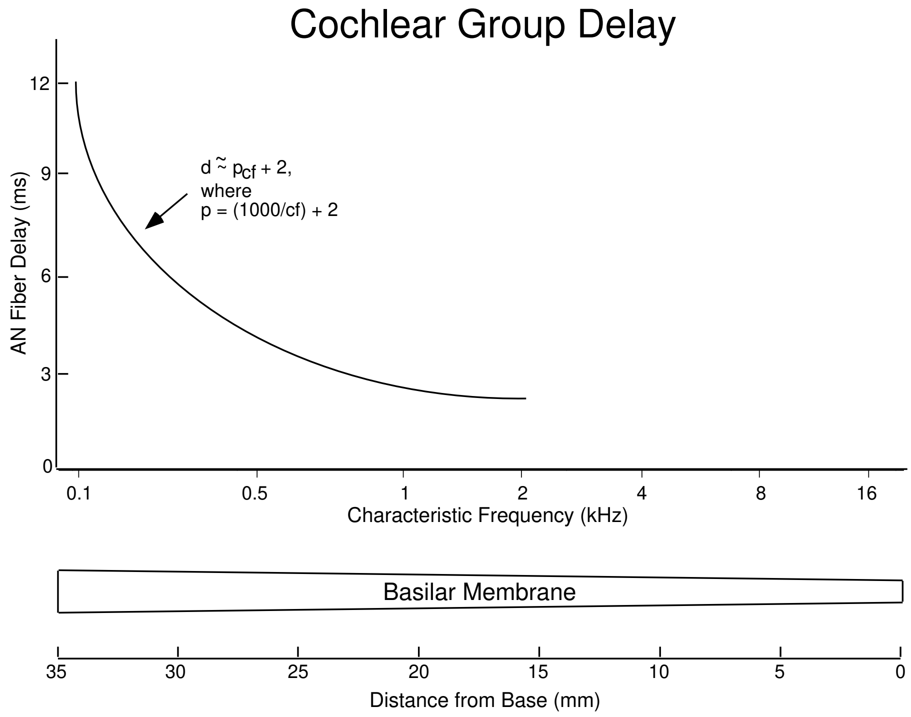

Figure 16.6: Cochlear Group Delay

An interesting fact is that the cochlear group delay (See Figure 16.6), which is a function of the traveling wave, is optimal (in a sense we'll soon see) for detecting coincident patterns evoked by harmonic signals.

Note that the cochlear group delay (i.e., the time delay between signal presentation and neural discharge), has a value for each frequency such that it is possible to detect periodicity using neurons that are temporally encoding frequency information. Consider Figure 16.7. Harmonically related frequencies are ploted on top of each other, but each is shifted to the right according to the cochlear group delay. Under the time-shifting of the cochlear group delay, peaks of the harmonically related frequencies have points that are highly correlated (the vertical dashed lines in Figure 16.7). The points are separated in time by the period of the fundamental frequency.

In theory, this idea could provide an explanation of the missing fundamental phenomena[SG95]. That is, outputs of each of these channels could be fed to multiple levels (a hierarchy) of autocorrelators (i.e., coincidence detectors) that, because of the way the signals have been shifted by the cochlear group delay, are time aligned so that the points of highest correlation across all the signals occur at a period identical to that of the missing fundamental. This periodic point-of-highest-correlation could then be used to reconstruct a temporally encoded fundamental frequency. The idea of *reconstructing the fundamental under the temporally-coded frequency paradigm* is the key result of this lecture.

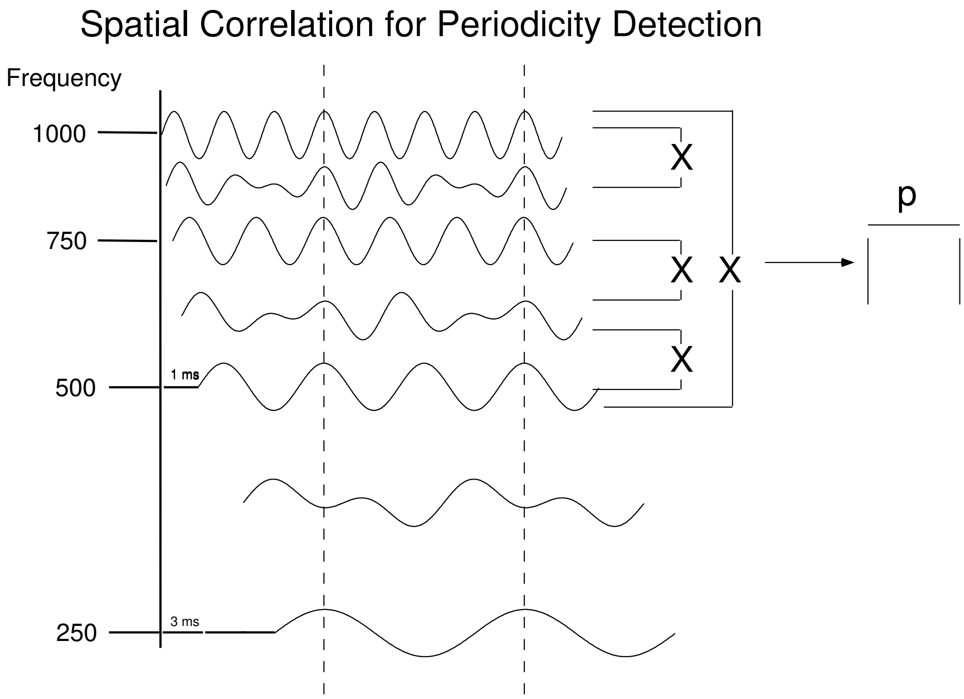

Figure 16.7: Spatial Correlation for Periodicity Detection

16.9 Conclusions

- Significance of the Traveling Wave
  Establishes Space - The time representation in the auditory periphery is likely to be an important factor underlying frequency selectivity.
- The Significance of Place
  Place provides the neural real estate over which neural coherence is analyzed and processed.
- The Significance of Time.
  Provides the statistical patterns from which coherence and novelty are inferred.
- Synthesis
  Place and time are but two sides of the same representational matrix, and are bound through the force of the group delay.
  So, the dichotomy between place and time is false.

16.10 Glossary

Key Anatomical Regions

Periphery

Cochlea - Inner ear. Includes organ of Corti, auditory nerve
Organ of Corti - Command post of peripheral transduction
Inner and outer hair cells - Sensory transducer of mechanics
Basilar Membrane - Origin of frequency selectivity
Tectoral Membrane - Overlies hair cells. Important interface
Auditory Nerve - Trunk line into the central auditory pathway

Central Pathway
Cochlear Nuclei - First integrative center.
Postero-Ventral Cochlear Nucleus - portion of above concerned with spectral & intensity information
Superior Olivary Complex - first binaural integration
Inferior Colliculus - Major brain-stem integration
Auditory Cortex - Very complicated, abstract processing

Key Terms and Concepts

Physical Systems
Automatic Gain Control - response adaptation across SPL
Dynamic Range - threshold to saturation range
Intensity - proportional to signal amplitude
Matched filter - enhanced response for concordant signals
Nonlinearity - e.g., compression, saturation, threshold, etc.
Phase Coding - time derivative

Perception
Frequency Selectivity - distinguish among spectral components
Loudness - perceived amplitude of signal
Pitch - signal's perceived base frequency
Timbre - signal's perceived spectral signature * (quite complex)

Physiology
Coincidence Detection[A82] - input simultaneity facilitates firing
Frequency Channel - coherent excitation across tonotopic domain
Integration - spatial and temporal
Micro-channel - small number of auditory nerve fibers innervating same inner hair cell
Neural Latency - initial discharge time relative to signal onset
Neural Synchrony across Channels - temporal pattern of activation
Phase-locking - neural firing correlated with temporal parameters
Place Principle - frequency coding derived from locus of excitation
Tonotopic Organization - Frequency maps onto spatial coordinates

References

Many additional references are included here which constitute a good starting point for exploring these issues further.

[A82] Abeles, M., (1982) "Role of the cortical neuron: integrator or coincidence detector?" Israel Journal of Medical Sciences 18: 83-92

[B60] Bekesy, G. von (1960) "Experiments in Hearing." New York: McGraw-Hill.

[Bi77] BILSEN, F. A. (1977) "Pitch of noise signals: Evidence for a central spectrum." J. Acoust. Soc. Am. 61: 150-161.

[Be76] BOER, E. DE(1976) "On the residue and auditory pitch perception." In: Handbook of Sensory Physiology V/3, W. D. Keidel and W. D. Neff, eds., Springer Verlag, Berlin, pp. 479-583.

[Br90] BREGMAN, A.(1990) "Auditory Scene Analysis." Cambridge, MA: MIT Press.

[CBC93] COOKE, M., BEET, S. AND CRAWFORD, M.(1993) "Visual Representations of Speech Signals." New York: Wiley.

[EGC] EDELMAN, G. M., GALL, W. E. AND COWAN, W. M.(1988) "Auditory Function: Neurobiological Bases of Hearing." New York: Wiley.

[E78] EVANS, E. F.(1978) "Place and time coding of frequency in the peripheral auditory system: Some physiological pros and cons." Audiology 17, 369-420.

[G88] GHITZA, O.(1988) "Temporal non-place information in the auditory-nerve firing patterns as a front-end for speech recognition in a noisy environment." J. Phon. 16:109-124.

[Gr88] GREENBERG, S.(1988) "Representation of Speech in the Auditory Periphery." Journal of Phonetics theme issue, Volume 16, number 1.

[Gr88] GREENBERG, S.(1988) "The ear as a speech analyzer," J. Phon .16: 139-150.

[SG95] S. GREENBERG, "Auditory Processing of Speech", To Appear. email: `<steveng@icsi.berkeley.edu>`.

[H89] HANDEL, S.(1989) "Listening." Cambridge, MA: MIT Press.

[He63] HELMHOLTZ, H. L. F. VON (1863) "Die Lehre von Tonemfindungen als Physiologie Grundlage dur die Theorie der Musik." Braunschweige: F. Vieweg und Sohn translated as On the Sensations of Tone as a Physiological Basis for the Theory of Music (4th ed.), by A. J. Ellis. New York: Dover (reprint of 1897) edition).

[Hu52] HUGGINS, W. H. (1952) "A phase principle for complex-frequency analysis and its implications in auditory theory." J. Acoust. Soc. Am. 24: 582-589.

[I86] IRVINE, D. R. F. (1986) "The Auditory Brainstem." Berlin: Springer Verlag.

[JGK] JENISON, R., GREENBERG, S. AND KLUENDER, K. (1991) "A composite model of the auditory periphery for the processing of speech based on the filter response functions of single auditory nerve fibers." J. Acoust. Soc. Am. 90:773-86.

[J80] JOHNSON, D. H. (1980) "The relationship between spike rate and synchrony in responses of auditory-nerve fibers to single tones." J. Acoust. Soc. Am., 68, 1115-1122.

[K84] KIANG, N. Y. S. (1984) "Peripheral neural processing of auditory information." In Handbook of physiology - the nervous system, volume III, sensory processes, part 2, (J. M. Brookhart and V. Mountcastle, editors), pp. 639-674. Bethesda: American Physiological Society.

[KGRH78] KITZES, L. M., GIBSON, M. M., ROSE, J. E., HIND, J. E. (1978) "Initial discharge latency and threshold considerations for some neurons in cochlear nucleus complex of the cat." J. Neurophysiol. 41: 1165-1182.

[La92] LANGNER G. (1992) "Periodicity coding in the auditory system." Hearing Res. 60:115-42.

[Le87] LEWIS, E. R. (1987) "Speculations about noise and the evolution of vertebrate hearing." Hearing Res. 25: 83-90.

[Li51] LICKLIDER, J. C. R. (1951) "A duplex theory of pitch perception." Experientia 7: 129-133.

[Li62] LICKLIDER, J. C. R. (1962) "Periodicity pitch and related auditory process models." Int. Audiol. 1: 1-36.

[M89] MOORE, B. C. J. (1989) "An Introduction to the Psychology of Hearing (3rd ed.)." London: Academic Press.

[O43] OHM, G. S. (1843) "Ber die definition des Tones, nebst daran geknupfter Theorie der Sirene und ahnlicher Tonbildener Vorrichtungen." Ann. D. Phys. 59: 497-565.

[Pi88] PICKLES, J. O. (1988) "An Introduction to the Physiology of Hearing (2nd ed.)." London: Academic Press.

[PF92] POPPER, A. N. AND FAY, R. R. (1992) "The Mammalian Auditory Pathway: Neurophysiology." New York: Springer Verlag.

[RG92] RHODE, W. S. AND GREENBERG, S. R. (1992) "Physiology of the cochlear nuclei", In: Popper, A. N. and Fay, R. R. (eds), The Mammalian Auditory Pathway: Neurophysiology. Springer Verlag, New York, pp. 94-152.

[RG94a] RHODE, W. S. AND GREENBERG, S. R. (1994a) "Lateral suppression and inhibition in the cochlear nucleus of the cat." Journal of Neurophysiology 71: 493-519.

[RG94b] RHODE, W. S. AND GREENBERG, S. R. (1994b) "Encoding of amplitude modulation in the cochlear nucleus of the cat." Journal of Neurophysiology 71: 1797-1825.

[RBAH67] ROSE, J. E., BRUGGE, J. F., ANDERSON, D. J. AND HIND, J. E. (1967) "Phase-locked response to low-frequency tones in single auditory nerve fibers of the squirrel monkey." J. Neurophysiol. 30: 769-793.

[SY79] SACHS, M. B. AND. YOUNG, E. D. (1979). "Encoding of steady-state vowels in the auditory nerve: Representation in terms of discharge rate", J. Acoust. Soc. Am. 66: 470-479.

[SBY88] SACHS, M. B., BLACKBURN, C. C. AND YOUNG, E. D. (1988) "Rate-place and temporal-place representations of vowels in the auditory nerve and anteroventral cochlear nucleus." J. Phon. 16: 37-53.

[S92] SCHOUTEN, M. E. H. (1992) "The Auditory Processing of Speech". Berlin: Mouton de Gruyter.

[SL88a] SCHREINER, C. AND LANGNER, G. (1988a) "Periodicity coding in the inferior colliculus of the cat. II Topographical organization." J. Neurophysiol. 60: 1823-1840.

[SL88b] SCHREINER, C. E. AND LANGNER, G. (1988b) "Coding of temporal patterns in the central auditory nervous system", In: Auditory Function: Neurobiological Bases of Hearing, G. M. Edelman, W. E. Gall and W. M. Cowan (eds.). New York: Wiley, pp. 337-361.

[SU86] SCHREINER, C. E. AND URBAS, J. V. (1986) "Representation of amplitude modulation in the auditory cortex of the cat. I. The anterior auditory field" (AAF). Hearing Res. 21: 227-241.

[S85a] SHAMMA, S. (1985a). "Speech processing in the auditory system I. Representation of speech sounds in the responses of the auditory nerve", J. Acoust. Soc. Am. 78, 1612-1621.

[S85b] SHAMMA, S. (1985b). "Speech processing in the auditory system II. Lateral inhibition and the processing of speech-evoked activity in the auditory nerve", J. Acoust. Soc. Am.,78: 1612-1621.

[S88] SHAMMA, S. (1988) "The acoustic features of speech sounds in a model of auditory processing: Vowels and voiceless fricatives", J. Phon. 16: 77-91.

[SL93] Slaney, M. and Lyon, R. F. (1993) "On the importance of time - a temporal representation of sound." In: Cooke, M., Beet, S. and Crawford, M. Visual Representations of Speech Signals. New York: Wiley, pp. 95-116.

[SG83] Srulovicz, P. and Goldstein, J. L. (1983) "A central spectrum model: a synthesis of auditory-nerve timing and place cues in monaural communication of frequency spectrum". J. Acoust. Soc. Am. 73: 1266-1275.

[WPF92] Webster, D. B. Popper, A. N. and Fay, R. R. (1992) "The Mammalian Auditory Pathway: Neuroanatomy". New York: Springer Verlag.

[W49] Weaver, E. G. (1949) "Theory of Hearing." New York: Wiley.

[YS79] Young, E. D. and Sachs, M. B. (1979) "Representation of steady-state vowels in the temporal aspects of the discharge patterns of auditory-nerve fibers". J. Acoust. Soc. Am. 66: 1381-1403.