

## Lecture 11: Perception of Loudness

Last time we saw that a physicist's answer to "how loud a sound is" was, "What you mean is, what is the sound's intensity, which is power per unit area."

The musician's answer is, "how loud does it sound to my ear?" which is a perceptual question. Some perceptual questions can be answered quantitatively, but others are harder to stick numbers to. Keep this in mind in what follows.

Loudness as perceived by your ear depends on several things. The most prominent is the intensity of the sound, but as we will discuss, the duration and frequency of the sound also have a bearing, and so does the frequency spectrum for sounds which are not sine waves. We should treat these one at a time, starting with intensity for sine waves.

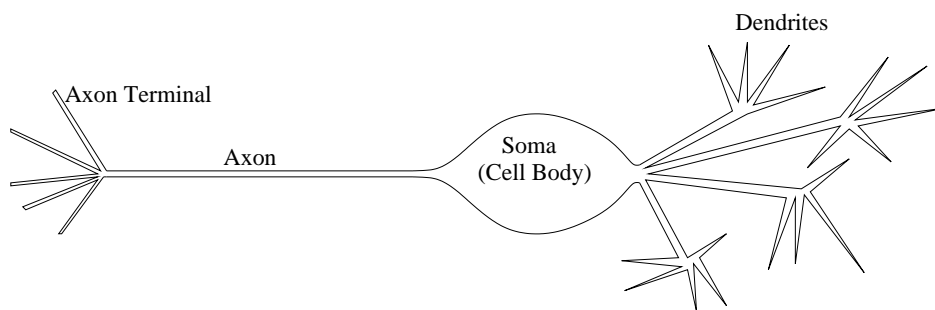
Listen to the first sound file for this lecture, which plays a tone at two loudnesses. How many times louder is the louder one? Everyone will agree about the qualitative answer of "which is louder?" Not everyone will put the same number on how many times louder it is, and no one's answer will be the actual ratio of intensities, which is 30. In fact, most people perceive the louder sound to be 3 to 5 times louder, rather than 30 times louder.

Therefore our loudness perception does not scale linearly with the intensity (sound power). Rather, a louder tone does not sound as much louder to us as it "really" is. Further, relative loudness is a qualitative perception which is a little hard to put a number on at all. Why and how does the nervous system do this?

The "why" is easy. Just as we hear sounds which occur in a wide range of frequencies, we hear sounds in a very wide range of loudnesses. Sometimes it is important to be able to hear that someone is breathing in the same room as you. Sometimes someone will shout in your ear. The sound intensity of the shout may be more than a billion (milliard,  $10^9$ ) times larger than the loudness of the breathing. You have to be able to usefully perceive both. (Your eyes have a similar problem. The difference in brightness between a sunny day and a moonless night is more than a factor of a billion. You have to be able to see things at night without being blinded in the day. If your vision perception were linear, you could not possibly do both.) If you really registered a sound 30 times louder than another as sounding 30 times louder, you would lose the quiet sounds behind the loud ones, and you could not handle as wide a range of loudnesses as you will encounter in your environment.

How does your ear do it? To see how, we have to go back and talk more about how nerves function.

Here is a bad cartoon of a nerve:



On one end the nerve has a bunch of stringy attachments called **dendrites**. These join together at a cell body (the fat lump) called the **soma**. Then there is a long cord, the **axon**, and a bunch more stringy attachments at the end, terminating in **synapses**, where they come up to the dendrites of other nerve cells. (They do not quite attach, but come close enough for electrical signals to cross from one to the other).

The dendrites are signal receivers. The cell body receives signals from all the dendrites, and “decides” whether or not (or, when) to send an electrical impulse down the axon. When an impulse is started on the axon, it travels along at about 10 m/s, reaches the axon terminals (all the stringy attachments at the end), and goes down each, to be received by the next nerve cells. The synapse is a connection which lets the signal hop from one nerve cell to the dendrite of the next.

The nerve signal going down the axon is always of the same size: a voltage of tens of millivolts (compare to computer logic, at a few volts, or the wallplug, at 120 volts in North America), with a tiny current, around  $10^{-12}$  Amps. The nerve cell does not send information via the size of the signal, only in the presence or absence of the signal, and in its timing.

The signals coming in from the dendrites are interpreted in different ways. Some dendrites, called **excitatory dendrites**, are interpreted by the soma as saying, “Fire!” Others, called **inhibitory dendrites**, are interpreted as saying, “Don’t fire!” The soma (cell body) does some kind of “voting” between these inputs to determine whether (and when) to send a nerve pulse down the axon. After such a fire, there is a period of about 1 millisecond when another firing cannot occur, and 2-4 milliseconds when firing is suppressed.

Each nerve cell connects to several hair cells, and possibly other nerve cells. They can serve many different purposes:

- “nervous” nerve cells, which fire whenever a few hair cells give them a signal;
- “normal” nerve cells, which require several hair cells to fire, to give a signal;
- “lazy” hair cells, which need almost all the hair cells to be firing before they will give a signal.

Further, since some signals can be inhibitory, a nerve cell might send a signal when it sees more activity in the lower-frequency hair cells than in the higher-frequency hair cells, or vice

versa. This gives extra information to help the brain recognize whether the excitation the hair cells are seeing is on the low or high frequency edge of the critical band (improving the ability to resolve where the critical band's center is).

For a quiet sound, only the “nervous” nerve cells fire. For a medium sound, the “normal” ones start to fire, and for a loud sound, the “lazy” ones fire too. This means that the number of nerve cells responding is not simply proportional to the intensity. It can be designed, by how many nerves of each type there are, to have whatever relation proves useful.

Roughly, the number of nerves transmitting the signal tells the brain how loud the sound is; twice as many nerve signals, twice the interpreted loudness. This is not a hard and fast rule, because how your perception of loudness works at the brain level also depends on a somewhat qualitative perception. However, averaging over many people answering questions like the one at the beginning of the lecture, one finds the

**Rough Rule of Thumb:**  $10\times$  increase in intensity is perceived as a  $2\times$  increase in perceived loudness.