What Is Sound? How Brains Make Hearing Sensations

Contents

Abstract

Brain transforms perceptual properties into patterns and motions of geometric-algebra vectors, making microscopic surface textures whose spatial and temporal properties are sensory experiences.

Keywords

area A1, attack, auditory neuron, azimuth, belt area, binauralism, characteristic frequency, cochlea, consonance, critical band, decay, dissonance, elevation, hair cell, harmonics, head-related transfer function, high-spontaneous fiber, interaural level difference, interaural time difference, lateral superior olive, loudness, low-spontaneous fiber, medial superior olive, octave, offset, onset, organ of Corti, parabelt area, phase locking, pitch, pitch width, place coding, place theory, superior olive, temporal code, temporal lobe, temporal theory, tone, tone chroma, trapezoid-body medial nucleus, volley code, volley theory

1. Anatomy

Vibration receptors send to auditory neurons, which send to cortical regions.

1.1. Hair cells

Inner-ear cochlea hair cells have vibration receptors that detect 20 Hz to 20,000 Hz compression-and-rarefaction longitudinal vibrations. The organ of Corti has 30,000 hair cells, with hairs ranging from short to long.

1.2. Neurons

Auditory neurons receive input from 10 to 30 hair cells.

1.3. Brain

Forebrain temporal lobe has regions for hearing.

Cortical area A1 auditory neurons align from low to high frequency {tonotopic organization}.

The adjacent belt area receives from area A1 and responds to complex sound features.

The laterally adjacent parabelt area receives from the belt area and responds to complex sounds and multisensory features.

Medial superior olive detects time differences between left-right ears and right-left ears. Lateral superior olive detects intensity-level differences between left-right ears and right-left ears.

Opposite-ear output goes to trapezoid-body medial nucleus, which lies beside pons lateral superior olive.

2. Physiology

Organ-of-Corti short hairs detect high frequencies, and long hairs detect low frequencies, so hair-cell-activity spatial distribution indicates frequency {place coding} {place theory}.

Temporal-lobe neurons receive from hair cells and find sound loudness and pitch.

2.1. Frequency

Auditory neurons have a frequency {characteristic frequency} at which they are most sensitive. If sound-wave frequency is above, or more than a quartertone below, characteristic frequency, auditory neurons fire at baseline frequency.

At frequencies below 800 Hz to 900 Hz, one neuron can carry sound information, and sound wave and neuron activity have same frequency {temporal theory} {temporal code}. Adjacent auditory neurons fire at same phase {phase locking} and frequency, because adjacent hair cells link and so push and pull at same time.

At 800 Hz, firing rate drops abruptly. From 800 Hz to 1600 Hz, at least two neurons carry sound information, and sound wave and neuron activity have linearly related frequency. Auditory-neuron subsets fire every other sound-wave cycle {volley theory} {volley code}. For example, one neuron firing at 600 Hz starting in phase with sound-wave frequency, and the other neuron firing at 600 Hz starting one sound-wave cycle later, can represent frequency 1200 Hz.

At 1600 Hz, firing rate drops abruptly. From 1600 Hz to 3000 Hz, at least three neurons carry sound information, and sound wave and neuron activity have linearly related frequency. Auditory-neuron subsets fire every third sound-wave cycle. For example, one neuron firing at 600 Hz starting in phase with sound-wave frequency, the second neuron firing at 600 Hz starting one sound-wave cycle later, and the third neuron firing at 600 Hz starting two sound-wave cycles later, can represent frequency 1800 Hz.

Above 3000 Hz, neuron sets respond to frequency, tone pattern, or intensity spectrum.

2.2. Intensity

Auditory neurons with the same characteristic frequency have three types.

Low-spontaneous fibers respond to high intensity of frequencies close to the characteristic frequency. Firing rate starts at less than 10 per second and rises with intensity.

High-spontaneous fibers respond to low intensity of frequencies within a wide range of the characteristic frequency. Firing rate starts at greater than 30 per second and rises with intensity (with maximum at a low intensity).

Mid-spontaneous fibers respond to medium intensity of frequencies within a medium range of the characteristic frequency. Firing rate starts at greater than 10 per second and rises to less than 30 per second.

2.3. Intensity-frequency distribution

Auditory-nerve-fiber activity distribution represents frequency, frequency-range {critical band}, and intensity.

Hearing performs limited-resolution Fourier analysis on sound frequencies and intensities [Friedmann, 1979]. Hearing perceptual processes [Kaas and Hackett, 2000] compare adjacent and harmonic frequency intensities, and integrate over many neurons, to filter frequencies to find their individual intensities.

3. Perceptual properties

People can detect loudness, pitch, tone chroma, pitch width, octaves, and harmonics. People can distinguish one million sounds.

People can hear sound waves of frequency 20 Hz to 20,000 Hz. Human hearing is most sensitive at frequency 1800 Hz. Above 5000 Hz, musical pitch is lost.

3.1. Loudness

Loudness relates to sound-wave relative intensity. People can distinguish 100 loudness levels.

3.2. Pitch

Pitch relates to sound-wave frequency. People easily distinguish tones and half tones, and can distinguish quarter-tones (whose frequencies differ by several percent) after learning. People can distinguish that a tone is slightly higher (sharp) or lower (flat) in frequency than another tone. People can distinguish 120 pitches.

Sounds with many high-frequency components seem shrill, strident, harsh, shallow, and/or thin. Tones with mostly low-frequency components seem dull, mellow, smooth, deep, and/or thick.

Full tones have many frequency resonances. Shallow tones have few frequency resonances.

3.3. Tone chroma

Tone chroma relates to sound-wave frequency range. Tones that share one octave have perceivable sound features. People can distinguish 10 tone chroma.

3.4. Pitch width

Pitch width relates to sound-wave frequency-intensity distribution around a frequency. People can distinguish 10 pitch widths. If all energy is at the frequency, pitch width is narrow. If energy is mostly at frequencies within a percent of the frequency, pitch width is wide. If energy is mostly at frequencies more than a percent of the frequency, pitch is lost, pitch width has no meaning, and sound is noise.

Clear tones have narrow frequency band. Unclear tones have wide frequency band. Noise has many frequencies.

3.5. Octaves

Two musical tones can have a frequency ratio expressible as 2^n, where n = -10 to +10. For example, middle-C frequency is 256 Hz, and high-C frequency is 512 Hz, so frequency ratio is 2^-1 = 1/2 or 2^1 = 2.

Hearing covers ten octaves: 20 Hz, 40 Hz, 80 Hz, 160 Hz, 320 Hz, 640 Hz, 1280 Hz, 2560 Hz, 5120 Hz, 10240 Hz, and 20480 Hz.

Within one octave are 7 whole tones: A, B, C, D, E, F, and G. Within one octave are 7 + 5 = 12 halftones: A, B-flat, B, C, C-sharp, D, D-sharp, E, F, F-sharp, G, and G-sharp. Within one octave are 24 quartertones.

3.6. Harmonics

Two musical tones can have a frequency ratio expressible using small integers. For example, middle-C and high-C have frequency ratio 1:2. Middle-C and middle-G have frequency ratio 2:3. Middle-G and high-C have frequency ratio 3:4.

Tone-frequency ratios of two tones within an octave are the same for all octaves. For example, high-C and high-G have frequency ratio 2:3.

For the seven whole tones in an octave (C, D, E, F, G, A, B), frequency ratios are D/C = 9/8 (D#/C = 6/5), E/C = 5/4, F/C = 4/3, G/C = 3/2, A/C = 5/3, and B/C = 11:6 or 15:8.

3.7. Consonance and dissonance

People hearing two tones report that they sound pleasingly consonant or less pleasingly dissonant.

Ratios with smallest integers in both numerator and denominator have consonance. Octaves are most pleasing. Frequency ratios 3/2 and 4/3 are pleasing.

Frequency ratios 5/4 and 8/5 are halfway between consonant and dissonant. Frequency ratios 6/5 and 5/3 intervals are halfway between consonant and dissonant.

Ratios with larger integers in both numerator and denominator have dissonance. Frequency ratios 7/6 and 12/7 intervals are dissonant. Frequency ratios 8/7 and 7/4 intervals are more dissonant. Frequency ratios 9/8 and 16/9 intervals are even more dissonant. Frequency ratios 16/15 and 15/8 intervals are most dissonant.

Tone ratios in octaves higher or lower than middle octave have same consonance or dissonance as the corresponding tone ratio in the middle octave. For example, high-G and high-C have ratio 3/2, the same as middle-G/middle-C.

Tone ratios between higher or lower octaves and middle octave have similar consonance as corresponding tone ratio in middle octave. For example, high-G and middle-C have ratio 3/1. Dividing by two makes high-G one octave lower, and middle-G/middle-C has ratio 3/2.

3.8. Attack and decay

Tones can rise quickly or slowly from background noise level to maximum intensity {attack} {onset}. Fast onset sounds aggressive. Slow onset sounds peaceful.

Tones can fall slowly or rapidly from maximum to background noise level {decay} {offset}.

3.9. Temperature

Warm tones have longer and lower attack and decay, longer tones, and more harmonics. Cool tones have shorter and higher attack and decay, shorter tones, and fewer harmonics.

3.10. Mixing

People can simultaneously hear different frequencies at different intensities. Sounds are independent, so hearing is an analytic sense.

Sounds do not have opposites.

3.11. Source location

Hearing determines sound location separately and independently of perceiving tones.

Having two ears {binauralism} allows calculating time, intensity, and phase differences between left-ear and right-ear sound streams, to locate sound source in space. Body and head, including pinnae and ear canals, transmit and absorb different frequency, elevation, and azimuth sounds differently {head-related transfer function}.

Hearing can calculate distance. Sound sources farther than 1000 meters have fewer high frequencies, because of air damping.

Hearing can calculate angle to right or left, from straight-ahead to straight-behind, in horizontal plane (azimuth).

Hearing can calculate height and angle above horizontal plane (elevation). People perceive lower frequencies as slightly lower than actual elevation. People perceive higher frequencies as slightly higher than actual elevation.

3.11.1. Timing differences

The same sound reaches right and left ear at different times {interaural time difference}, because distances from source location to ears differ. Hearing can detect several microseconds of time difference.

Medial superior olive detects time differences between left-right ears and right-left ears. To find distances, two receptor outputs go to two different neurons, which both send to difference-finding neuron, to make an opponent system.

Interaural time difference uses frequencies lower than 1500 Hz, because they have no body damping.

Interaural time difference and interaural level difference work together to eliminate direction ambiguity. Slight head movements can eliminate any remaining direction ambiguity.

3.11.2. Intensity differences

The same sound reaches right and left ear at different intensity levels {interaural level difference}. Intensity difference reflects stimulus distance, approaching or receding sounds, and body sound damping. Level difference can be as small as 1 dB.

Lateral superior olive detects intensity-level differences between left-right ears and right-left ears. To find distance, two receptor outputs go to two different neurons, which both send to difference-finding neuron, to make an opponent system.

Opposite-ear output goes to trapezoid-body medial nucleus, beside pons lateral superior olive, which inhibits same-ear lateral-superior-olive output.

Intensity differences due only to sound distance, or to approaching or receding sounds, are useful up to one or two meters (because, beyond two meters, differences are too small to detect).

Beyond one or two meters, hearing uses intensity differences of frequencies higher than 1500 Hz to determine space directions and distances. Pinnae and head bones absorb sounds with frequencies higher than 1500 Hz, according to their frequency-related dampening function. Pinnae and head-bone damping differs on right and left, depending on source location.

Interaural time difference and interaural level difference work together to eliminate direction ambiguity. Slight head movements can eliminate any remaining direction ambiguity.

3.11.3. Phase differences

People cannot hear phase differences, but hearing can use phase differences to locate sounds.

3.11.4. Interference

Hearing can detect more than one source and frequency from one location. Hearing can have interference from more than one source.

4. Relations to other senses

Hearing, temperature, and touch involve mechanical energy.

Sound is fast vibration, while touch can have slow vibration. Sounds are longitudinal mechanical vibrations. The lowest sound frequencies, 20 Hz to 30 Hz, are also the highest vibrations detectable by touch. Below 20 Hz, people feel pressure changes as vibration, rather than hearing them as sound. Sound vibrates eardrum and other body surfaces but is not felt as touch, unless very loud.

Vision and hearing share same perceptual space.

Noise sound and white color are similar in that they involve multiple frequencies.

5. Sound sensations

Hearing detects sound intensity, frequency, and frequency distribution.

Tones have categories but vary continuously over the frequency range.

Tones do not mix, and people can simultaneously hear different frequencies at different intensities.

Note 1: Sound waves are longitudinal waves, with compressions and rarefactions in air (or another medium). Molecules oscillate as sound waves pass through the medium. Loudness depends on compression pressure and so on the force that caused the original vibration. Media can carry waves of many frequencies.

Note 2: Higher compression pressures give media molecules higher speeds but also proportionally more distance, and molecule collisions are elastic collisions, so frequencies stay constant.

Note 3: Elastic collisions are very-high-speed electromagnetic interactions, so sound waves travel so quickly that previous compressions do not interfere with later compressions.

Note 4: For the same wave frequency, greater amplitudes have higher amplitude-change rates. For the same wave amplitude, higher frequencies have higher amplitude-change rates. For different wave amplitudes, higher frequencies have higher ratios of amplitude-change rate to amplitude. Therefore, the ratio of amplitude-change rate to amplitude indicates wave frequency, within a time interval one-half wave period. Perhaps brain auditory systems use attack (or decay) to help find sound frequency.

6. Sound descriptors

Hearing perceives sound duration, loudness (from intensity), attack and decay (from intensity), pitch (from frequency), pitch width (from frequency distribution), tone chroma of tones in same octave (from frequency distribution), and harmonics and consonance-dissonance (from frequency distribution).

Low-frequency sounds can be dull, mellow, smooth, rounded, and/or thick. High-frequency sounds can be shrill, strident, harsh, jagged, and/or thin.

Sounds with many frequency resonances sound full. Sounds with few frequency resonances sound shallow.

Sounds with a narrow frequency band sound clear. Sounds with a wide frequency band sound unclear. Sounds with many frequencies sound like noise.

Two similar tones can sound sharp or flat compared to each other.

Sounds with low frequency and no attack and decay have warm temperature. Sounds with high frequency and attack and decay have cool temperature.

7. Spatiotemporal properties and patterns

Hearing perceptual-property spatiotemporal patterns are vibrations.

Sound sensations sound like vibrations.

Perhaps, sounds feel like they have a fundamental vibration, with different tones on that vibration, like modulation of a fundamental frequency. The sound of fundamental vibration comes from the feeling of mechanical vibration at 20 Hz to 30 Hz, which is like a hum. Higher frequencies sound higher than the sound of the fundamental vibration because they are multiples of the fundamental vibration, so they sound double, 3/2, and so on the fundamental sound. Therefore, the first sound comes from mechanical flapping, and higher-frequency sounds sound like multiples of that sound, and so sound higher.

Note: Perhaps sound sensations vibrate at a rate that is the logarithm of the actual vibration frequency, and so along a linear scale from 1 to 120.

8. Machines

Machines can simulate sound sensations using a microscopic-surface-texture array with elements that oscillate radially at the same frequency as the stimulus (or its logarithm). More elements represent higher loudness.

References

Friedmann, Imrich (1979) *The Human Ear*. Burlington, NC: Carolina Biological Supply.

Kaas, Jon H.; and Hackett, Troy A. (2000) Subdivisions of auditory cortex and processing streams in primates. *Proceedings of the National Academy of Sciences USA*, 97, 11793-11799.

Note: The Bibliography of Hearing, Sound, and Audition and the Consciousness Bibliography of 10,000 books and articles, with full journal and author names, is available in text and PDF file formats at http://www.outline-of-knowledge.info/Consciousness_Bibliography/index.html.

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