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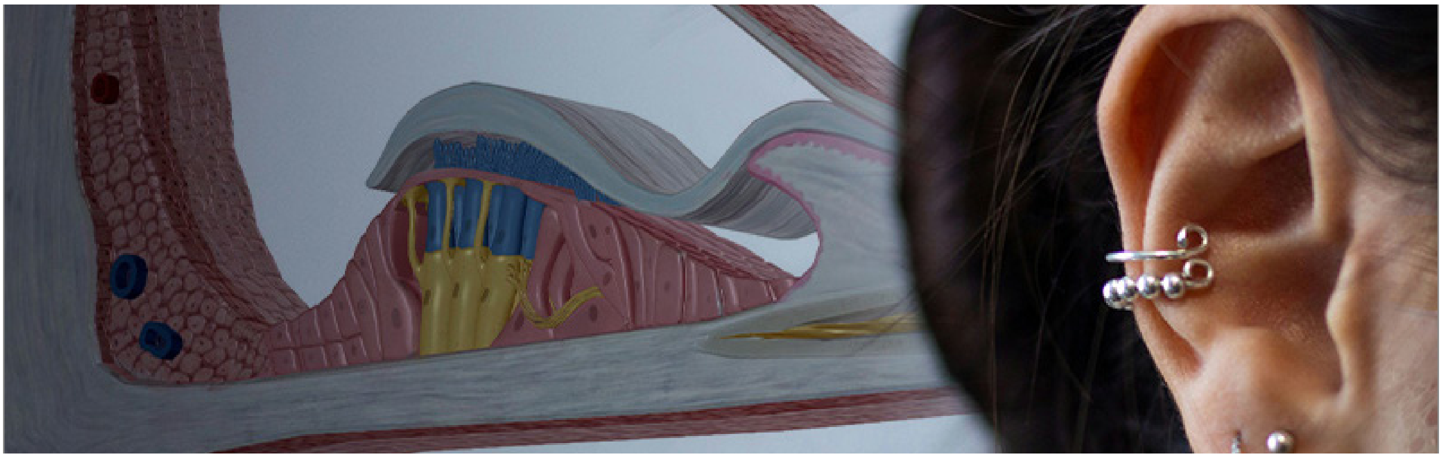


How do we hear?

Nurunisa Akyuz, Chuck Phillips

Your ear can detect movements smaller than atoms and turn them into music, voices and laughter. How does it work?

From tiny vibrations to the sounds of life

Imagine someone calling your name from across the playground.

How does the sound of your name travel through the air, enter your ear and suddenly become something your brain can understand?

Our sense of hearing has an extraordinary dynamic range: we can detect sounds as soft as a whisper and can tolerate sounds as loud as a rock concert or fireworks near the threshold of pain.[1] This is a remarkable dynamic range. Hearing is also unique among our senses because it allows us to detect sounds coming from all directions at once. Even in the dark, when we cannot see what is around us, hearing helps us to stay aware of our environment.

We rely on hearing every day: to communicate with other people, to enjoy music and to notice danger in the dark. But how does the ear transform tiny vibrations in the air into signals in our brain?

From sound waves to the inner ear

Sound begins as vibrations in the air, known as sound waves. When someone speaks, plays music or closes a door, the air molecules vibrate back and forth, creating pressure waves that travel through the air.[2] The outer part of your ear, also called the pinna, acts like a funnel. It catches these waves and guides them into the ear canal, where they hit the eardrum. The eardrum then begins to vibrate, just as the skin of a drum does when it is tapped (figure 1).

These vibrations are then passed to the three tiny bones in the middle ear called the ossicles. The stapes, one of the three bones, is the smallest bone in your body, smaller than a grain of rice. These bones act like a system of levers that amplify the vibrations and send them deep into the ear.

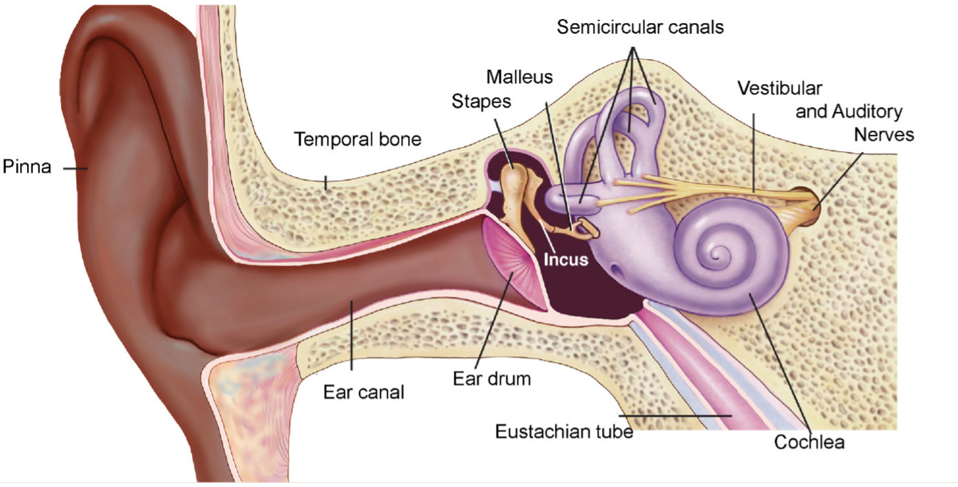


Figure 1: The anatomy of the ear is shown. Sound waves enter the outer ear and travel through the ear canal to the eardrum. Vibrations then pass through the middle ear bones to the spiral-shaped cochlea in the inner ear.
Image courtesy of NIDCD/NIH

The vibrations finally reach the cochlea, a spiral-shaped and fluid-filled organ (figure 1). Its name comes from the Greek word for snail, because of its spiral shape.

The cochlea's hidden keyboard

Inside the cochlea, sound vibrations travel through fluid and stimulate different regions along the spiral. Scientists sometimes say that your ear contains a piano played in reverse.[3] On a real piano, you press a key to make a particular note. In the cochlea, the reverse happens: different frequencies stimulate different locations along the spiral:

- low sounds vibrate near one end of the spiral (apex);
- high sounds vibrate near the other (base).

The frequency of a sound determines its pitch (i.e. how high or low it sounds), while its intensity determines its loudness. For example, a soprano singer can produce very high-pitched notes, which have a higher frequency than the notes produced by a typical speaking voice. Humans can hear sounds between roughly 20 and 20 000 hertz (Hz). One vibration per second is one hertz; 20 Hz means 20 vibrations per second, and so on. Our hearing range covers the notes of a piano and even extends slightly beyond them. However, our ability to hear the highest frequencies gradually declines with age, which is why older adults sometimes have trouble hearing high-pitched sounds.

Try this! Listening for different pitches

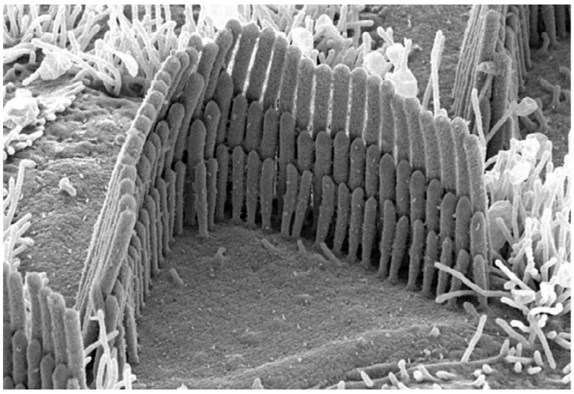
Many smartphones or computers can play tones at different frequencies.

- Try listening to tones at 100 Hz, 1 000 Hz, and 10 000 Hz. Which tone sounds lowest? Which sounds highest? Can everyone in your class hear the 10 000 Hz tone? You may notice that younger people often hear higher frequencies better than adults.
- Now try two tones that are very close together, such as 2000 Hz and 2050 Hz. Our ears are remarkably good at distinguishing small differences in pitch.

Turning vibrations into electricity

The cochlea contains about 15 000 sensory cells called hair cells. They are named for the tiny hair-like protrusions on their surfaces called the stereocilia (figure 2). When the vibrations reach the cochlea, these stereocilia move back and forth. These movements cause tiny molecular gates near the tips of the stereocilia to open. These gates are called ion channels. When they open, charged particles (ions) rush into the cell, converting the movement of the stereocilia into a tiny electrical signal. These electrical signals carry information about the sounds we hear.

For decades, scientists knew that these gates existed; they could measure them opening. But nobody knew what the gates were made of or what they looked like. It was one of the longest-standing puzzles in sensory biology. In 2018, researchers found strong evidence that a protein called TMC1 forms part of the pore – the tiny opening through which the ions pass.[4] As the ions enter, they change the voltage across the hair cell membrane, producing an electrical response. This electrical change causes the hair cell to release a chemical messenger called glutamate onto nearby auditory nerve endings. The auditory nerve carries this information as electrical impulses that travel to the brain. What began as invisible vibrations in the air has now been transformed into signals that the brain can interpret as a voice, music or laughter.



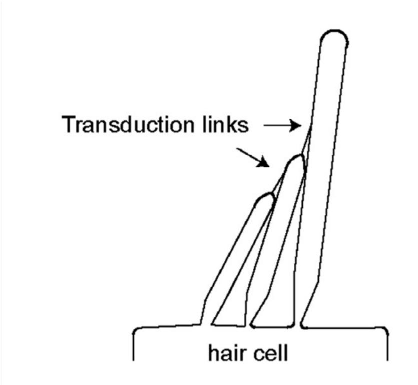


Figure 2: Hair cells inside the cochlea are shown. The tiny hair-like structures on top of these sensory cells, called stereocilia, deflect when sound vibrations move the fluid inside the cochlea. This deflection leads to opening of molecular gates that generate electrical signals sent to the brain. Left: A scanning electron microscope (SEM). Right: A schematic of a hair-bundle; bending towards the tallest stereocilia tensions the transduction links (tip links between the stereocilia)

Image: Left: adapted from Dr David Furness/wellcome collection; CC BY-NC 4.0. Right: adapted from Akyuz N et al./Current Biology

Did You Know?

All cells carefully control the ions inside and outside their membranes. Pumps and other transport proteins use energy to create unequal concentrations of ions on the two sides of the membrane. When ion channels open, ions flow across due to the built-up concentration and electrical gradient, changing the cell's voltage and creating an electrical signal. The ions are then transported back so that the cell can respond again. Hair cells, nerve cells and muscle cells all rely on this same basic principle.

Scientist spotlight

In pioneering experiments in the 1970s and 1980s, A. James Hudspeth and David P. Corey used tiny electrodes to record from hair cells while gently moving their stereocilia. They discovered that even extremely small movements produced an almost immediate electrical response. Their work helped establish that mechanical force directly opens ion channels in the hair-cell membrane – long before scientists knew the molecular identity of those channels.[5]

A built-in sound amplifier

For a long time, scientists thought that the ear worked like a microphone: sound waves enter, hair cells detect them and the brain receives the signal. However, researchers later discovered something surprising: the inner ear is not just a detector of sound. Hair cells can also boost faint sounds by adding energy back into the vibrations, making them easier to detect. This built-in amplifier allows our ears to detect incredibly quiet sounds.[6] Sometimes this amplifier becomes so active that the ear produces its own tiny sounds, called otoacoustic emissions.

Did You Know?

- The ear can detect vibrations smaller than a billionth of a meter!
- The difference between the quietest sound we can hear and the loudest we can tolerate is about a trillion-fold in intensity.
- Healthy ears sometimes produce tiny sounds called otoacoustic emissions.
- Doctors use otoacoustic emissions to test hearing in newborn babies.

Image: Anastasiya Badun/Unsplash, Public Domain

Hearing across the animal kingdom

Humans are only part of the story. Across the animal kingdom, hearing systems have evolved to detect the sounds that matter most for each species. For example:

- elephants communicate using infrasound, very low-frequency rumbles that can travel long distances;
- bats produce ultrasound, extremely high-frequency sounds that allow them to navigate and hunt insects in the dark using echolocation.

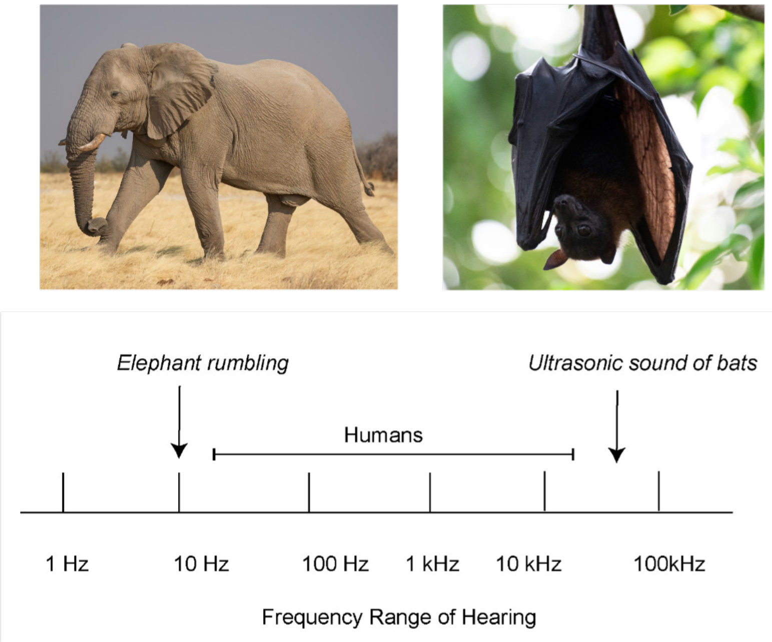


Figure 3: Different animals detect different parts of the sound spectrum. Elephants communicate using very low-frequency sounds (infrasound), while bats use extremely high-frequency sounds (ultrasound) for echolocation. Humans hear frequencies between about 20 and 20 000 Hz.

Images: Elephant: Giles Laurent/[Wikimedia Commons](), CC BY-SA 4.0. Bat: Frida Lannerström/[Unsplash](), Public Domain. Graph: courtesy of the authors

Although all these systems look very different, they often rely on the same basic idea: tiny mechanical vibrations are turned into electrical signals.

Protecting our hearing

Our ears are remarkably sensitive, but they are not invulnerable. Very loud sounds can damage sensory hair cells of the inner ear, and in humans these cells do not regenerate. Remarkably, birds and some other vertebrates can generate them, which has made this process a major focus of hearing research. Loud noise can also destroy the delicate connections between hair cells and the auditory nerve fibres. The risk of hearing damage depends both on sound intensity and the duration of exposure. This is why listening volume matters when we use headphones and earbuds, and many devices now allow users to monitor their listening levels or set a maximum volume. Hearing aids also amplify sounds but selectively: they boost the frequencies that a person struggles with and must be properly fitted so that their output stays within safe limits.

How do scientists study hearing?

The parts that detect sound are extremely small, far too small to see with the naked eye. Because of this, scientists use special tools to understand how hearing works. This includes:

- **powerful microscopes**: these reveal the delicate structures inside the ear. Some microscopes can even show molecules, the tiny proteins that act as the sound-detecting gates.
- **electrophysiology**: researchers place extremely fine glass electrodes near cells to measure the electrical signals produced when hair cells detect sound.
- **fluorescent labels**: glowing molecules can be attached to proteins, enabling scientists to see where they are and how they move inside cells.
- **genetics**: studying genes linked to hearing loss helps researchers identify which molecules are essential for hearing.

Why is this important?

Understanding how healthy hair cells detect sound can also help scientists understand what goes wrong when hearing is damaged:

- develop better hearing aids and cochlear implants;
- create gene therapies that restore hearing;
- design new medicines to protect hearing from damage;
- build bio-inspired sensors based on the incredible sensitivity of the ear.

By studying the inner ear, scientists are not only learning how we hear; they are also discovering ideas that could shape future technologies. And it all begins with something very small: tiny moving hair-bundles that turn the vibrations of the world into the sounds of life.

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Resources

- Use sound-detecting robots to explore how sound waves behave in different settings: Ladas V, Stylos G, Kotsis KT (2025) Explore the properties of sound waves by using robotics. *Science in School* **73**.
- Discover how to use Faraday's law to build a loudspeaker: Anta A, Goiri E (2018) Hearing waves: how to build a loudspeaker. *Science in School* **45**: 38–42.
- Learn what it feels like if numbers and sounds had colours: Tilot A (2016) Blended senses: understanding synaesthesia. *Science in School* **38**: 8–11.
- Learn about the barrier that protects the brain by separating it from circulating blood: Jiang Y (2017) Guardian of the brain: the blood-brain barrier. *Science in School* **42**: 18–22.
- Find out about a technique based on the photoacoustic effect that can make medical imaging less dangerous: Czuchnowski J, Prevedel R (2019) Photoacoustics: seeing with sound. *Science in School* **47**: 14–18.

AUTHOR BIOGRAPHY

Nurunisa Akyuz is a molecular biophysicist investigating how the inner ear converts sound vibrations into electrical signals that the brain can understand. Her research helped establish the identity of the ion channel that enables hearing.

Chuck Phillips is a biochemist working on how proteins interact to enable sensory processes. His work has explored how proteins in the hearing machinery work together to allow the inner ear to detect sound.