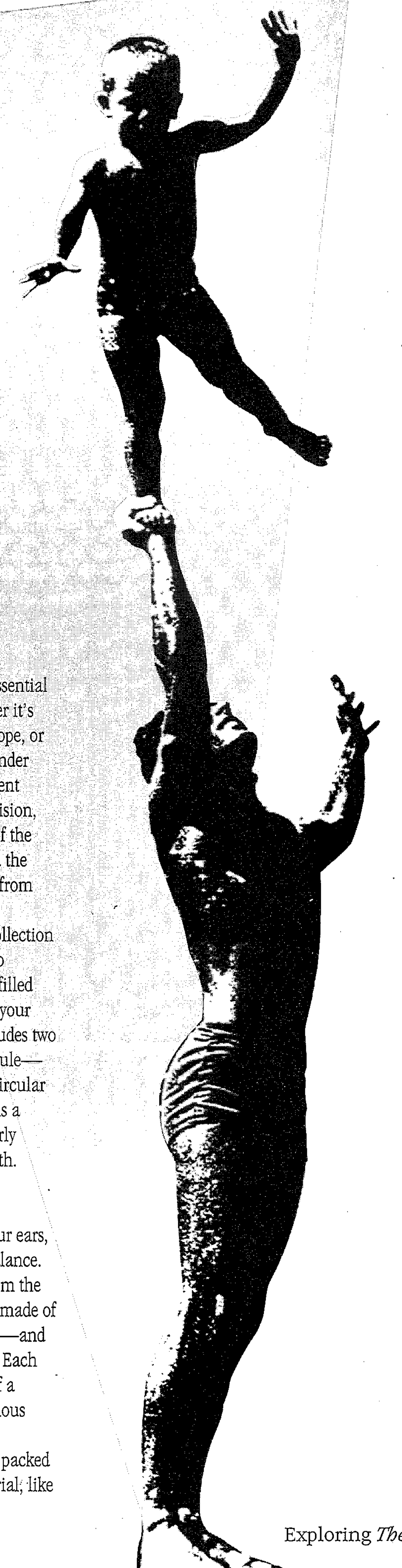
Listening to Gravity

by Paul Doherty

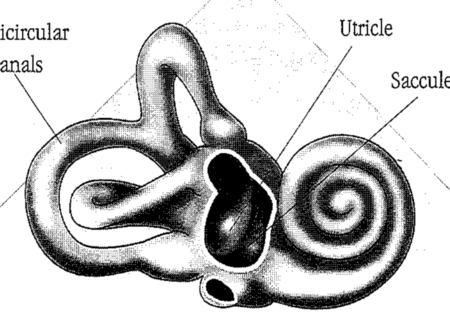
You've got rocks in your head and they help you keep your balance.



Cross-country skiing by starlight was eerie, but fun. I was aware of the sights and sounds of the world whizzing past me. But I was blissfully unconscious of other, far more important signals that were continuously being sent from my inner ears to my brain—signals that were crucial to my ability to remain balanced over my skinny skis. As I turned down the gentle slope, the sensors of my inner ear provided my brain with information on my acceleration, my orientation with respect to gravity, and my continuously changing rotation.

Most of us remain blissfully unaware of our vestibular system—the balance mechanisms of our inner ears. These mechanisms are essential to any activity requiring balance, whether it's skiing, riding a bicycle, walking a tightrope, or simply standing on your own two feet. Under most circumstances, you use three different systems to sense your orientation: your vision, your proprioception (your body's sense of the tensions and shapes of your muscles and the pressures on your skin), and the signals from your inner ear.

Besides containing an astonishing collection of hearing apparatus, your inner ear also includes an array of hair-studded, fluid-filled tubes and containers that help you keep your balance. This part of your inner ear includes two gel-filled bags—the utricle and the saccule—and three mutually perpendicular semicircular tubes. This tangle of tubes and sacs forms a plumbing system so complicated that early researchers called it the auditory labyrinth.

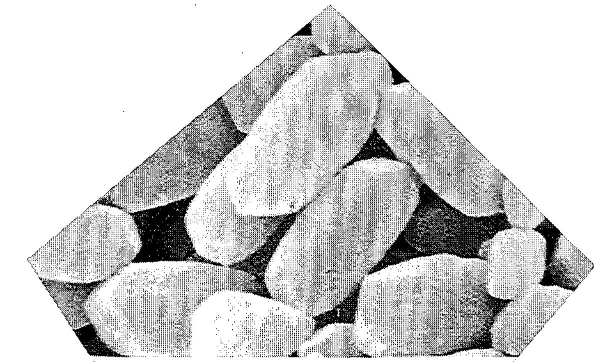


Your semicircular canals, the three fluid-filled arches of your inner ear, sprout from small bulges filled with sensor cells and then wrap around the larger bulges of the saccule and utricle. The diagram on pages 6-7 shows how this system, which is responsible for your balance and orientation, relates to the other organs of your ear.

Rocks in Your Head

You have rocks in your head—in your ears, that is—and they help you keep your balance. The rocks, called ear dust or *otoliths* (from the Greek words for "ear" and "stone"), are made of calcium carbonate—just like limestone—and are about three times denser than water. Each one is tiny, about a tenth the diameter of a human hair. They're packed in a gelatinous mass inside the utricle and the saccule.

In one of the bags, a set of otoliths is packed in a horizontal layer of gelatinous material, like pebbles sprinkled onto a Jell-O–covered cookie sheet. If you tilt the cookie sheet down, gravity will drag the pebbles in the direction of the tilt. That's essentially what happens when you tilt your head forward: gravity pulls the otoliths toward the front of your head and your vestibular system detects the change. Your vestibular system is so sensitive to the motion of the otoliths that it can detect a tilt as slight as one degree from the vertical—a rotation of just 1/360 of a circle.



This is an image of human otoliths, the "rocks in your head" that respond to gravity and acceleration. Each rock is about a tenth the diameter of a human hair.

Your otoliths are sometimes called your body's "gravity sensors," but they actually sense a combination of gravity and acceleration. This combination of information can lead to sensory illusions. The next time you have an aisle seat near the tail of a large aircraft, look forward along the aisle as the plane begins to accelerate for takeoff. You will sense that the aisle is tilting uphill, away from you. Look out the window and you will see that the plane is still level relative to the horizon. As the plane accelerates forward, the inertia of the rocks causes them to move back relative to your inner ear—just as they would if your seat and the aisle were actually tilting uphill.

Dancing Hairs

Electron microscopes have only recently revealed how the tiny motions of otoliths and gelatin are converted into the nerve impulses that give your brain information about your orientation. Hair cells, which grow into the gelatin from below, cluster together in bundles, with short hairs on one side and long hairs on the other. The top of each hair is connected to a neighboring hair by a very thin filament.

When the hairs are standing straight up, nerves at the base of each cluster fire about one hundred times each second. When gravity or acceleration moves the otoliths so that they pull the bundles of hairs toward the tallest hair, the connecting filaments pull open channels that allow ions (electrically charged atoms) to leak into and out of each hair cell. This causes the nerve connected to the bundle to triple its firing rate. When the hairs are bent the other way, toward the shorter hairs, the nerve stops firing. The clusters of hair cells are arranged so that the pattern of nerve signals encodes the direction of the tilt of your head.

Your body automatically responds to these nerve signals. When your body tips forward, for example, the nerves signal the tilt and the muscles at the back of your neck tighten to keep your head from falling forward.

Since all this happens automatically, how can you tell that you have sensors in your ears? As long as your vestibular system is working properly, you'll never be aware of it. This sense works at a subliminal level, outside your conscious control. People who have been buried in snow report that they cannot tell which way is up. Blinded and pressed upon from all directions, they cannot use light or pressure to sense their orientation. Though their vestibular apparatus is still working, they cannot "hear" its messages.

To test these reports, I went into a swimming pool and covered my eyes, rolled up into a ball, breathed out a little air (so I wouldn't float), and had a friend spin me around. When I stopped rotating, I had a weird feeling in my stomach that told me I was not right-side up. Even so, I could not point toward the surface of the pool.

Splashing Fluids

Have you ever gotten off a carnival ride and felt like the world was still spinning? You owe that dizzying sensation to the second part of your vestibular apparatus: your semicircular canals.

You have three semicircular canals. Each canal is filled with a fluid called endolymph. Where each of the canals attaches to the body of your inner ear, there is a bulge containing a blob of hair-cell-filled gelatin. Whenever you move your head, the fluid flows around the canal and over the gelatin. It pushes the gelatin to the side, bending the hair cells and changing the firing

Try This!

Experience Formication

You hear sound and sense acceleration because hair cells in your ear bend, which changes the firing of nerves. The short hairs on your skin allow you to experiment with a similar mechanoreceptor system.

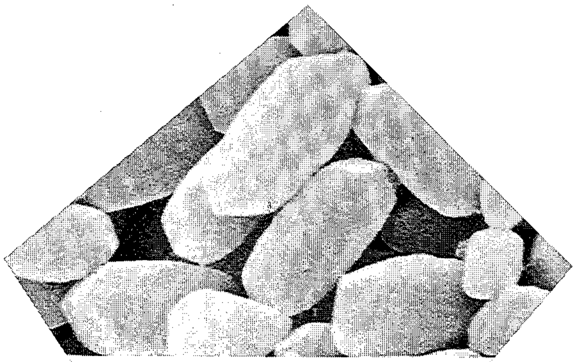
To Do & Notice

- Find a partner and a toothpick.
- Close your eyes.
- Have your partner use the toothpick to gently bend one of the hairs on your arm. Notice the feeling produced by the bending hair.

What's Going On?

The hairs on your arm are mechanoreceptors—they detect mechanical deformation. When the hairs are bent, nerves near the base of the hair send signals to the brain. This is similar in operation to the sensory hair cells in your ear, which generate signals when they are deformed.

Formication is the name of the sensation of insects crawling over your skin, bumping into and deforming hairs. It comes from the word *formica,* which is Latin for "ant."



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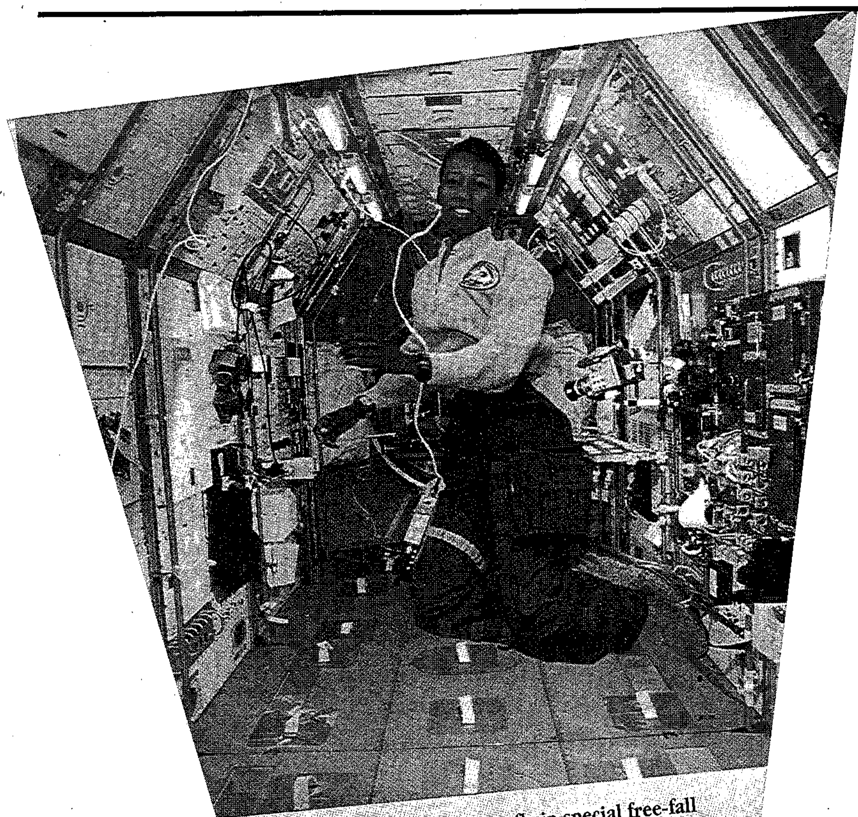


By training on aircraft that fly in special free-fall trajectories, astronauts can experience the sensations produced by apparent weightlessness.

rate of the nerves. By detecting the acceleration as you start to fall or spin, your semicircular canals provide your brain with an early warning of a fall. This gives your muscles time to react.

To understand how your semicircular canals detect changes in rotational motion, imagine a glass of water with inside walls that are coated with thick, fuzzy moss. Picture the glass in the center of a lazy Susan and then mentally spin it around. When the water is at rest, the moss grows straight out from the walls. When you start to rotate the glass, the water doesn't move at first. The base of the moss moves with the glass and the tips of the moss stay behind in the fluid. The moss bends—just like the hair cells in your semicircular canals. The hair cells send a message to your brain that rotation has begun.

If you keep rotating the glass long enough, the water starts to rotate, too, and the moss straightens out. The same thing happens in your semicircular canals. Spin long enough, and the fluid starts to spin and the hairs straighten. When you stop spinning, the fluid will keep moving, bending the hairs in the opposite direction. That's why you feel like you're still rotating after you stop a prolonged spin. For a while, the fluid in your inner ear keeps on moving.

Spinning isn't the only way to get the fluid in your semicircular canals moving. A jet of cold water sprayed into your ear can also make you dizzy. By suddenly cooling some of the fluid in the semicircular canals, you set up convection currents, warm fluid rising up through cooler fluid. These currents cause dizziness—which is why doctors are careful to use body-temperature water to flush out your ears.

Each of your three semicircular canals detects movement in a different direction. The semicircular canal that detects right-left rotation also provides some of the nerve impulses that control your eyes. If you watch someone who's just stopped spinning around, you may be able to see his or her eyes move to the side and then jump back, over and over again. This eye motion, called nystagmus, is caused by signals from the fluids of the inner ears. Dancers and skaters learn to live with these signals. But for some people, the uncomfortable result is a bout of motion sickness.

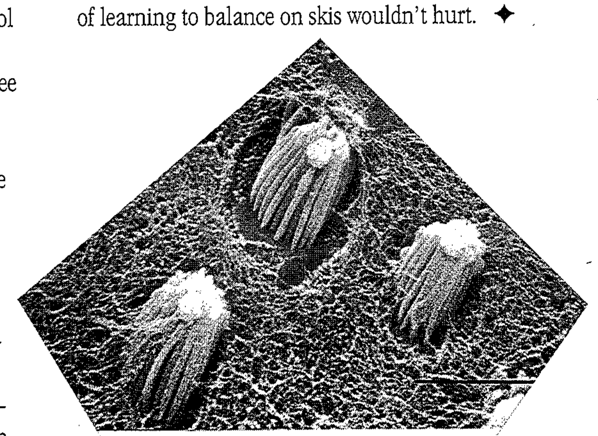
We know that people often get motion sickness when signals from their eyes and ears disagree. This is a particular problem for astronauts, who often work in free-fall. Even though they may not be able to see that they are falling, their inner ears sense their free-fall condition. If you've ever tried to read while riding down a twisty road, you may have experienced the same kind of eye-ear confusion. Your eyes report that you are stationary—at least with respect to your book—yet your inner ears are reporting on the accelerations and rotations of your body. The conflicting signals can make you feel ill.

Gravity Makes Itself Heard

Under normal conditions, you remain unaware of the workings of your vestibular system. But if it breaks down, you'll notice instantly. Years ago, an ear infection scrambled my balance systems. Until it cleared up, skiing became impossible; even standing up was difficult.

On this glorious night, however, as I skied through the stillness of the starlit terrain, everything seemed to be working perfectly. More than simply hearing the world around me, my inner ear was also detecting signals from within my body—listening to gravity, acceleration, rotation. After years of practice, I had learned to use this unconscious flow of information to help me remain balanced over my skis, and I was confident in my own abilities.

Then, suddenly, I was falling. For a fraction of a second, rocks jiggled, fluids sloshed, and hair cells danced inside my head as I briefly entered free-fall, then crashed into a heap in the snow. As I struggled to my feet and brushed the snow from my body, I knew that a few more years of learning to balance on skis wouldn't hurt. ✦



Hair cells in the vestibular system are grouped into clusters. Before this image was made, the gelatin that normally covers these cells was removed.

Ask Us

Mary K. Miller

I've noticed that almost any object with some color in it will become darker and more vivid when it's dipped in water. I'd like to know why this happens. Does the same explanation hold true for similar effects when shellac, varnish, or oil are substituted for water?

—Olyn Garfield
San Rafael, California

We probably all have childhood memories of picking up a stone at the beach and sticking it in the water to make the colors pop out. Some lucky kids even had motorized rock tumblers to turn lackluster pebbles into shiny, brightly colored treasures. Wetting or polishing rocks makes them more vivid because it smooths out the naturally rough texture of a rock and reduces light reflections from its surface. When you reduce surface reflections, the colors in a rock can shine through.

When white light penetrates the surface of a rock or other colored object, it interacts with pigments underneath. The light that reflects back—that is, the light that you actually see—is colored by these pigments. When light hits a bumpy surface, it's scattered in all directions before it reaches the pigments. The scattered white light from the surface of the rock dulls, or *desaturates,* the colors in the rock in much the same way that rub-on wax dulls the color of a car before it's buffed. If you pour water or another clear liquid on the rock, you essentially smooth out the surface and eliminate the scattered light reflections. Light reflections from the now-smooth surface are concentrated in one direction, allowing the true colors of the rock to come through. You can see these concentrated reflections as white highlights on the surface of a wet or polished stone. Shellac, oil, varnish, and wax all work like water on a beach stone by eliminating scattered light reflections.

Why do soft things get hard and crispy when you fry them in oil? I know that food gets hard when it dries out, but how can something dry out when you're immersing it in hot liquid?

—Isador Shud
Pulaski, New Jersey

Foods *do* dry out when you drop them in hot oil, which is why soft, mushy things, like raw meatballs or doughnuts, get hard and crispy after frying. "Things are mushy because they're wet," says Harold McGee, author of *The Curious Cook*. "When you immerse food in hot oil, the heat draws the water out [of the food]. You're essentially dehydrating food from the outside in." If you leave the food in hot oil too long, all the water escapes and you're left with a shriveled-up piece of hard, burnt food.

You also asked how something can dry out when you're immersing it in hot liquid. "There are liquids and then there are liquids," says McGee. "Oil doesn't mix well with water and can be heated above the boiling point of water (212°F or 100°C)." Because there's no water mixed in with the oil, food isn't moisturized as it fries. Instead, the super-hot oil literally drives the water out. "All the bubbles and spatters in the deep fryer is water escaping from the food," McGee says.

In the Fall 1993 issue of *Exploring: In the Dark,* someone asked about how magnets affect TV screens and you wrote that the damage they can cause is permanent. In fact, a magnetized screen can be fixed by applying an AC field from a small induction motor (like a small fan). It's picky of me, perhaps, but I don't want people to think that their TVs are irreparably ruined when they're not.

—Todd Johnson (SciTech Member)
Aurora, Illinois

You're right, a small AC field can demagnetize a TV screen and will usually erase the discoloration caused by a magnet. We haven't tried using a fan motor, as you suggest, but we have used a demagnetizing coil from an electronics store to fix the problem. Also, many higher-end TVs come equipped with a "de-gaussing" circuit that automatically demagnetizes the screen every time you turn on your TV.

However, if the magnet you wave in front of the TV is strong enough, you can permanently magnetize the metal strips mounted along the edge of the screen. When that happens, it's very difficult to demagnetize the TV and eliminate the damage.

A note to our readers

Many of you have written to give us alternative answers to some of the problems presented in *Exploring: Puzzles and Problems* (Summer 1993). In fact, we've received more letters about *Puzzles* than about any other issue in years. It's nice to know you're out there and enjoying the magazine. We'd like to thank all of you for your creativitity, your enthusiasm, and for taking the time to let us know about your own explorations. ✦

Reviews & Resources

Tools & Toys

When I was in third grade, we came back from Christmas vacation to find that there was a new kid in Mrs. Balser's class. His name was Larry Whiteman, and he had a buzz-cut and the biggest stick-out ears any of us had ever seen. And he could wiggle them. It's the only time in my life I can remember paying a whole lot of attention to my ears. Everyone in my class spent hours and hours looking in the mirror at their ears, trying to get them to wiggle. Timmy Luddington thought he could, but we all agreed that only his forehead was really moving.

I felt a surge of that old ear-mania return when I picked up *Bizarre and Beautiful Ears* (**$14.95**) and found out that moths have their ears under their wings! This book's full of dozens of full-color photos and hundreds of amazing facts about the ears of twenty different animals —from moths and mosquitoes to dolphins and humans.

If you want more detail about human ears, I recommend *Ears Are for Hearing* (**$4.50, paper**). It's a book by Paul Showers, illustrated by Holly Keller, that tells practically everything about ears and hearing for kids ages 5–9. It explains what sound waves are, how they travel to your ear, and how your brain processes them. For older kids, ages 8–12, *Come to Your Senses* (**$9.95, paper**) by Milan Tytla has an excellent chapter (with experiments and activities) on how your ears affect balance and motion, and another on how you hear.

What about people whose ears don't process sounds? *Seeing Voices* by Dr. Oliver Sacks (**$8.95, paper**) is a fascinating and provocative look at deaf people and deaf culture, including the development and implications of American Sign Language. Many people who are only partially deaf use hearing aids, which have microphones and speakers a lot like telephones. With the **Build Your Own Telephone Kit** (**$25.00**), you can discover how sounds are transmitted from one place to another as you construct your own, working phone. This kit comes with a book of instructions and phone facts, a circuit board, microphone, keypad, cords, and everything else you need. After you put your phone together (no tools required), just plug it into any phone jack and send your voice across the neighborhood or around the world.