

SCOPE, SEQUENCE, and COORDINATION

A National Curriculum Project for High School Science Education

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** Not part of the NSF-funded SS&C project.

Student Materials

Learning Sequence Item:

912

Animal Behavior

September 1996

Adapted by: Lucy Daniel

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Science as Inquiry

Acting on Impulse**How does a planarian respond to environmental stimuli?****Overview:**

Most of us have seen animals that have been taught tricks. Dogs can easily learn to shake hands, play dead, and roll over. How do we teach an animal something? Can all animals be trained to respond in certain ways? In this activity you are going to investigate the behavior of planaria and possibly their ability to be trained. Planaria are flatworms that are very soft, so handle them with care.

Procedure:

Use the dropper to remove one planarian from the culture and place it in a test tube. Add aquarium water to the test tube until it is nearly full, then insert the stopper. Draw a line at the middle of the test tube and hold the tube horizontally until the planarian has moved to the center. Place the test tube “stopper-end up” in the test tube rack. Observe the planarian for 10 minutes, recording how much time the planarian spends in each half of the test tube.

Hold the tube horizontally again, and when the planarian has moved to the center, place the tube “stopper-end down” in the rack and observe the behavior of the planarian for another 10 minutes.

After the planarian has again been allowed to move to the center of the test tube, lay the tube on a sheet of white paper. Make the same observations for another 10 minutes.

Finally, after the planarian has returned to the middle of the test tube, place an aluminum foil square over the rounded end of the tube. Record the behavior of the planarian for 10 minutes.

Questions:

1. What stimuli did the planarian respond to in this activity?
2. Compare your results with those of other groups in your class. Did all the planaria behave similarly? What were the similarities or differences?
3. What may be an advantage of these behaviors in planaria?
4. How could you use this type of behavior to train planaria to move through a maze?

Science as Inquiry

To Squirm Like a Worm**How do earthworms respond to stimuli?****Overview:**

Earthworms, or nightcrawlers, are often used as bait in fishing. Like planaria, they have behavior patterns that may be helpful to them. In this activity you will observe, time, and record these earthworm patterns. Be sure to keep your hands wet while working with the earthworms and wash your hands when you have finished.

Procedure:

Add moist sand to a baking pan until it is about $\frac{2}{3}$ full, then cut a piece of cardboard to cover half of the pan. Position three earthworms on top of the sand, with the anterior (front) ends of the worms facing in the same direction. Cover the pan, placing the cardboard over the posterior (back) ends of the earthworms, leaving the anterior ends exposed. Record your observations.

Remove the cover and reposition the earthworms in the pan as before. However, this time cover the anterior ends, leaving the posterior ends exposed. Record your observations.

Repeat this process of positioning and covering the worms (first the posterior, then anterior) except this time shine a flashlight on the pan once the pan has been covered. Observe, time, and record the behavior of the worms.

Repeat the process again, but this time replace the flashlight with a 100-watt lamp and record your observations.

Remove the cover from the pan and return two of the earthworms to the instructor's storage area. Place your remaining earthworm in the center of the pan. Using the cotton swab, draw a line—using the lemon juice and water solution—in front of the anterior end of the earthworm. Observe and record the behavior of the earthworm. Next, draw a line with the solution in front of the posterior end of the earthworm and observe and record its behavior.

Repeat this process using straight lemon juice and record the earthworm's behavior.

Questions:

1. Summarize the reactions of the earthworms.
2. To what stimuli were the earthworms reacting?
3. Did the strength of the stimuli affect the behavior? How?
4. Do the anterior and posterior ends respond equally to light?
5. How is the earthworm's response to light and chemicals helpful in preserving the species?

Science as Inquiry

Let Me Enlighten You**How does light intensity affect the eye?****Overview:**

The pupil is the dark opening in the center of the colored part of the eye (the iris). Here you will investigate the pupils of your eyes and your pupils' reaction to light.

Procedure:

Work in pairs. Student one should close his eyes for 10 seconds. As soon he opens his eyes, student two should carefully observe what happens and record her observations. What changes in the eyes of student one can be observed? How long do the changes occur?

Student one again closes both eyes for 10 seconds, this time holding his hand (or a card) vertically along the side of his nose, so that a light striking the left eye will not strike the right eye. He then opens his eyes, and student two shines the flashlight into his left eye and records her observations. Repeat the procedure using the right eye.

Next, student one should try to control the changes that were observed. Can one consciously control these changes? Repeat the procedures above and note any changes.

Switch roles and repeat the entire process—so that student one can observe what happens to the eyes of student two.

Questions:

1. How did eyes change when exposed to light?
2. What results did you get when one of you tried to control what was changing in your eye?
3. Some responses are described as automatic. How does this term apply to what you have observed?

Science as Inquiry

Fast Fingers**Can reaction time be measured?****Overview:**

How fast can you react? Insurance companies base their rates on just that ability. Certain age groups have been shown to react more slowly. Here you will test your own ability to react, what we call reaction time.

Procedure:

Work in groups of three. Student one should hold the ruler between her thumb and index finger while student two holds the ruler at the 1-cm end. As student one keeps her eyes on the bottom of the ruler (the end closest to her), student two releases the ruler. Student one must try to catch the ruler as soon as it is dropped. Students one and two continue to drop the ruler nine times, for a total of 10 trials. Student three records the distance the ruler has fallen for each trial.

Repeat the procedure (switching places) for the two other members of the group.

Questions:

1. How did response time vary within the class?
2. How did the number of trials affect ability to react quickly?
3. How does reaction time compare with the changes in the eye that you observed in the previous experiment?

Science in Personal and Social Perspectives

SEEING IN THE DARK

You've visited this world. We all have. It's just the other side of sunset—the dimly lit world of twilight and night.

There's a world where there are no colors—just black and white and shades of gray. In this world, the normal rules don't apply: you see best if you avert your eyes, looking slightly to one side of what you want to see. You can make out general shapes, but the details are left to your imagination. A chair piled with clothes becomes a lurking monster; a tree branch becomes a reaching hand.

You've visited this world. We all have. It's just the other side of sunset—the dimly lit world of twilight and night. You may not have noticed the change in your vision when your eyes adjusted to dim light. It's easy to overlook a shift that's been happening all your life. But if you pay attention, you'll realize that the world looks very different at night. The experiments described here show you how you can explore your ability to adapt to darkness and see in the dark.

The Edge of Night

In total darkness, of course, you can't see. But the world is rarely completely dark. In a situation that most of us would call dark—on a moonless night when the only light is from the stars, for example—you can see reasonably well. But your view by night is not the same as your view by day. When the lights are dim and your eyes adapt to

Letting in the Light

The pupil of your eye responds immediately to changes in light. To observe this change, all you need is a mirror and a dimly lit room with a bright light you can switch on.

Stand in the dimly lit room and look at your pupils in the mirror. Switch on the light, and watch your pupils shrink. Turn the light off, and watch your pupils expand again. Your pupils open up to let in more light and close down to shut out light.

If you watch the pupils of other people's eyes, you may notice that the pupil sometimes changes size even when there has been no change in lighting. Under normal lighting, have a friend focus on something far away. Watch her eyes as she shifts her gaze to something nearby. Chances are, you'll see her pupils shrink. Closing down your pupil helps you see nearby objects in better focus. When gathering light is more important than a sharp image, your pupil opens up. When there's enough light to sacrifice a little to improve focus, your pupil may close down. The older you get, the more your pupil works to compensate for your failing vision.

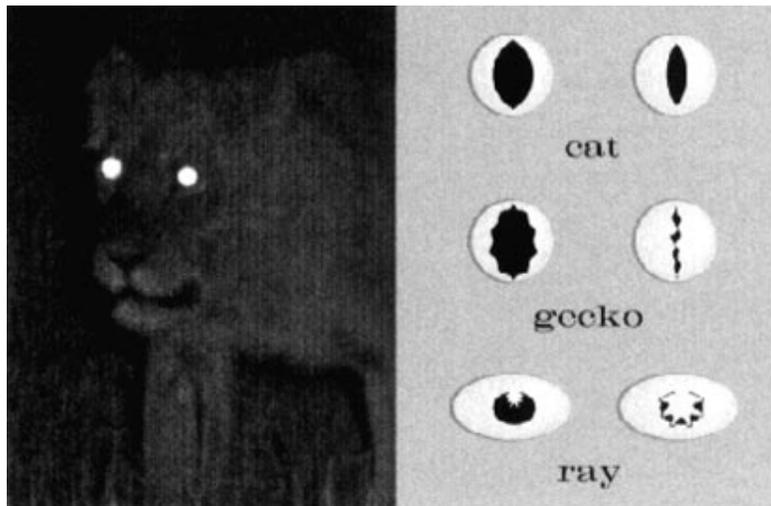
darkness, your vision changes—dramatically and fundamentally. It's not just that you can't see as well, though that's what most of us notice. You see differently.

It takes your eyes some time to adapt to dark-

By Pat Murphy © The Exploratorium, 1993. First published in *Exploring Magazine*, Vol. 17, No. 3, Fall 1993, pp. 8–13, by the Exploratorium, San Francisco, Calif. To learn more about the Exploratorium, visit the Exploratorium website (click here on [Exploratorium](#)).

ness. Go for a walk on a country road some moonless night and you'll find that for the first few minutes you can't see very well at all. After five minutes in the dark, your eyes begin to adapt and you can see better. The sky looks lighter than the trees; you can make out vague shapes, see the path in front of you. Over the next half hour or so, your eyes continue to adapt to the darkness. After a prolonged period in the dark, you may be able to see well enough to spot a light as dim as a candle ten miles away.

As your eyes adapt to the dark, they undergo a number of changes. Some happen quickly; others take place slowly. Together, these changes make your eyes much more sensitive to light, allowing them to gather information from the dim light of the moon or the stars. When fully adapted



A cat's eyes shine at night because light reflects from the tapetum lucidum, a layer of shiny material at the back of the eye. Animals that need to see in the dark and the daylight need pupils that can close almost entirely. The ray, a deep-sea fish, sleeps at the ocean's surface by day.

to darkness, your eyes may be up to one hundred thousand times more sensitive to light than they are on a sunny afternoon.

Exploring in the Dark

Follow these instructions and you'll learn a little more about what you can and can't see in the dark. You'll need a dark patch for one eye. I made one out of gauze, medical tape, and black duct tape. Or you can tie a strip of black fabric around your head and over one eye. Anything that blocks out the light will work fine. You'll also need a room that you can make dark.

Cover one eye with your dark patch and wear it for ten to twenty minutes. While your eye is covered, it's adapting to the darkness.

Now go into the darkened room and take off the patch. Look at the room through one eye, and then through the other. The eye that was covered with the patch is adapted to the darkness and can see much more clearly than the eye that was exposed to light.

Does your dark-adapted eye see as clearly as your eyes do in the light? Take a careful look at the room around you. The outlines of furniture will be less distinct than they are in the light; the pictures on the walls will be dark rectangles.

When you have both eyes open, you may find your half-adapted vision a little disconcerting. I found myself blinking repeatedly, trying to see as clearly with one eye as I could with the other.

People who explore caves use this trick to get one eye used to the dark before they enter a cave. Since researching this article, I always close one eye when I get up to go to the bathroom in the middle of the night. The eye that's closed remains dark-adapted, and when I return to my dark bedroom I don't trip over shoes and books on my way back to bed.

Disappearing Colors

To test your ability to see colors in dim light, you'll need the patch that you used for "Exploring in the Dark," a room that you can make dark, some pieces of colored paper (wrapping paper or construction paper will do), an assortment of colored pencils, markers, or crayons, and some blank paper.

Put your patch over one eye and wait fifteen to twenty minutes, as you did for "Exploring in the Dark." Go into your darkened room and remove the patch. Or, if you'd prefer, you can simply sit in your darkened room for fifteen or twenty minutes, waiting for both eyes to adapt to the darkness.

Now take your colored pieces of paper and sort them according to color as best you can. On each piece you might want to write the color that you think it is. Take your colored pencils, markers, or

crayons and write, with each one, the color that you think it is. Turn on the lights and see how you did.

Chances are you didn't do very well. The world that you see in dim light is similar to the world of the achromat, that rare person who has no color vision at all. Knut Norby, a vision researcher who was also an achromat, wrote of his childhood experiences with crayons: ". . . I always confused the colors, breaking all the conventions and 'rules' about what were the 'correct' colors to use: I would happily color the sky light green, yellow, or pink; the grass and leaves orange or dark blue; the sun white or light blue, and so on. I was always corrected in my choice of colors by those who knew better, and, eventually, I gave up painting and coloring my drawings."

Letting in the Light

Next time you look in a mirror, examine your eyes closely. In the center of each colored iris is a round black opening called the pupil. Light enters your eye through the pupil. The bigger the pupil is, the more light that can enter your eye.

The moment that you step into darkness, the muscles of the iris relax to let your pupil open wide and let in more light. (See "Letting in the Light.") At its smallest, the pupil of the human eye is just over one thousandth of a square inch in area. At its largest, the area of the pupil is up to fifty times that size and lets in up to fifty times more light.

Your pupils respond quickly to any change in lighting. In just one-fifth of a second, they can expand from their smallest size to their largest. Your pupils are constantly adjusting to minor changes in lighting, expanding when a cloud passes over the sun or shrinking when you walk from a shadowy hallway to a brightly lit room.

The expansion of your pupils is the first thing that happens as your eyes adapt to darkness, but it's not enough to explain the dramatic increase in your eyes' sensitivity over time. Other changes,

taking place deep inside your eye, make it more sensitive to the light that the pupil lets in.

At Night, All Cats Are Gray

After your pupils have opened wide, your eyes continue to adapt to darkness. Deep inside your eye, certain cells are becoming more sensitive to light so that they can take advantage of the dim light that's available. You can't see these changes, but if you are patient, you can see the results, as your eyes become more sensitive to light and your view of the world changes. (See "Exploring in the Dark.")

To understand how your eyes adapt to darkness, you need to know why you can see at all. You see when light stimulates the light-sensitive cells in your eye. These cells are called photoreceptors—photo is the Greek word for "light." The photoreceptors of your eye are part of the retina, a layer of cells at the back of your eyeball. The photoreceptors detect light and the patterns that it forms on the retina, then send this information to your brain via the optic nerve.

Your retina contains two kinds of photorecep-

Slow Sight

In dim light, your eyes respond more slowly than they do in bright light. That can create a dramatic illusion called the Pulfrich effect, after Carl Pulfrich, the man who discovered it.

To create this illusion, you'll need a pair of sunglasses or a dark filter, a friend or helper, a piece of string about one yard long, and something white that you can tie or tape to the string. (I used a rock wrapped in a piece of white paper.)

Use your white object and the string to make a pendulum. In a well-lit place, have your friend stand a few yards away from you and swing the pendulum back and forth, perpendicular to your line of sight. Cover one eye with the dark filter or with one lens of the sunglasses. Keeping both eyes open, watch the pendulum. Does it still look like it's swinging back and forth, or has its path

changed? Now move the filter to the other eye. How does the path of the pendulum change?

When you covered one eye with a filter, the pendulum's path apparently changed from a back-and-forth motion to an ellipse. When you switched the filter from one eye to the other, the direction of the ellipse changed—if it was traveling clockwise, it switched to counterclockwise, and vice versa.

In dim light, your eyes respond a little bit more slowly than they do in bright light. As a result, the eye with the filter sees the pendulum where it used to be—a fraction of a second behind the position observed by the eye without the filter. Your brain combines the views of your two eyes to make a three-dimensional picture of the world. By changing the view that one eye sees, you change the picture that your brain creates.

tors: cones and rods. Cones operate in daylight and let you see colors; rods are more sensitive to dim light than cones, but can't distinguish color. Each of your eyes contains about 6.5 million cones and 125 million rods.

Your eyes' sensitivity to light changes over time. In the first five minutes after you step into a dark room, your eyes' sensitivity increases dramatically. Then the rate of change slows and levels off to a plateau. After a few minutes, sensitivity begins to increase once again; over the next half hour or so, your eyes gradually become more and more sensitive to light.

That plateau indicates a shift from one system of photoreceptors to another. During the first five minutes that you are in the dark, all the photoreceptors in your eye—both rods and cones—are gradually becoming more sensitive to light. As the cones become more sensitive, you can see dimmer colored lights. But at the plateau, the cones reach their limit—they are as sensitive to light as they can get. At that point, the rods take over. The rods are much more sensitive to light than the cones. And the longer you keep them in the dark, the

more sensitive they become. The plateau marks the point where your eyes switch from relying mainly on the cones to relying on the rods.

In bright light, your vision depends on the cones; in dimmer light, you use the rods. When you are depending on the rods for your view of the world, your color vision goes away. The rods register the pattern of light on the retina—they can distinguish bright light from dim light—but they don't distinguish one color from another.

Next time you're in a darkened movie theater, take a look at your clothing. To your dark-adjusted eyes, a yellow shirt may appear to be pale gray, red will look black, and other colors will appear as various shades of gray. But the bright pictures on the movie screen and the glowing EXIT signs will still appear in color. Even when you are seeing the world with your rods, your cones are there. If there's a light that's bright enough to stimulate them, you'll see that bright light in color, even though you see the rest of your surroundings in shades of gray. (See "Try This: Disappearing Colors.") If you try to sort colors in dim light, you may notice a strange shift. In bright light, reds and

Seeing Stars

On a clear, moonless night, far from the city lights, go out and look at the stars. Find a star that's fairly faint, and look at it directly. You might choose Alcor, the smallest star in the handle of the Big Dipper. Now look slightly above or below the star. When you aren't looking directly at the star, it should look brighter. If you search, you may be able to find stars that you can see only when you look above or below them. If you look at these faint stars directly, they seem to disappear.

yellows often look brighter—more intense—than blues. But in dim light, blues often look brighter than reds. Fire engines are painted red so that they'll be bright and easy to see. And they are—during the day. But on a dark night, a bright red fire engine fades to black (which is why some towns are painting fire engines bright yellow-green, a color that's bright in dim light as well as in daylight).

Back in 1825, Czechoslovakian physiologist Johannes Purkinje noticed that colors changed with shifts in light. He observed that two painted posts, one red and one blue, were equally bright when he saw them at noon. At dawn, however, the blue post looked brighter than the red one. Dubbed the Purkinje shift, this subtle perceptual change happens when your eyes shift from relying primarily on cones to relying primarily on rods. Rods only detect whether a light is bright or dim. But they are not equally sensitive to all colors of light. Viewing a red light and a blue light of equal brightness, the rods will see the blue light as brighter. They'll barely detect the red light at all.

Night pilots and astronomers have turned the rods' low sensitivity to red light to their advantage. During World War II, pilots preparing for night missions wore red goggles in the ready room and in the cockpit when it was illuminated. Because the red light kept the rods in the dark, the rods began adjusting to darkness before the lights actually went out. In astronomical observatories,

illumination is provided by red light—so that the astronomer's night vision will not be disrupted.

The Monster in the Closet

Under red light, you can read, write, and make out the details of your surroundings. Switch off the red light and shift to rod vision, and the type on the page becomes illegible. In a darkened room, you have to fill in the details as best you can. The process can transform the shadowy clothes in the closet into the monsters of childhood nightmares. Blame those night monsters on an overactive imagination—and, of course, the rods in your retina.

Rods and cones are not evenly distributed across your retina. Near the center of the retina there's a small region called the fovea, where the cones are packed tightly together and there are no rods at all. Not only are there more cones, they also transmit more information to your brain. Typically, one nerve fiber carries the signal from just one cone. As a result, the fovea gives you a very detailed view of the world.

Outside the fovea, there are fewer cones and many rods. Unlike the cones, the rods at the periphery of the retina tend to merge their signals. A single nerve fiber may carry information from as many as 600 rods. Your rods provide a coarser, less detailed view than your cones, partly because they provide your brain with less information about the light they detect. You can think of the view pro-

Cat's Eyes

The ordinary house cat is active at night as well as during the day. If you have a cat, you can observe a few of the ways that a cat's eyes are different from your own—adaptations that provide the cat with a clear view of the world in dim light.

If you look in the mirror, you can see that your own pupils are round. In dim light, your cat's pupils may also look round. But take a look at your cat's pupils the next time the cat is basking in the sun, and you'll see that they are slit-shaped, rather than round. The cat's pupils are slit-shaped because the cat not only needs to see well in the dark, it also needs to close out the glare of daylight. A round pupil can't close down as much as a slit-shaped pupil can.

You've probably noticed that the eyes of certain animals gleam when they are caught in the headlights of your car. If you have a flashlight and a cat, you can duplicate this at home. Stand five or six feet away from your cat in a darkened room. Hold the

flashlight near your face, and shine it at your cat. The cat's eyes will reflect the light back to you, apparently glowing in the dark. Try the same thing with a friend and you'll see that the person's eyes won't glow.

Back behind the light-sensitive cells in the eye of a cat is a layer of tissue that reflects light. This reflective layer is called *tapetum lucidum* (Latin for "luminous carpet"). The cat's eyes have two chances to detect light—once when it enters the eye and once when it reflects back out. This makes the cat's eyes more sensitive to light—but results in an image that's a little blurry. The cat's eye has gained sensitivity to light but has sacrificed the ability to see fine detail.

Your own eyes don't glow like a cat's. Behind the photosensitive cells of your retina is a layer of dark pigment that absorbs light. When light shines into your eyes, very little of it reflects back out.

vided by the cones as a pointillist painting created with a fine brush and bright colors—and the view provided by the rods as the same painting, recreated with a wide brush and shades of gray. Details that are distinguished in the first view are lost in the second.

The distribution of rods and cones in the retina also explains a trick that night watchmen and astronomers use. To spot an intruder in a dark warehouse or a dim star in the night sky, they never stare directly at what they're trying to see. Instead, they look slightly above or below the object of interest. Try this yourself: in dim light, you'll see an object more clearly if you don't look at it directly. (See "Seeing Stars.")

When you stare at something, you are focusing its image on the fovea. In daylight, that's great: the densely packed cones in the fovea give you a very detailed, colored view of the world. But in dim light, your cones don't function. Since the fovea lacks rods, it's virtually blind in the dark. When

you look just above or below something, the image falls outside the fovea, on the periphery of the retina, where there are more rods than cones, giving you a much better view.

Slow Sight

Many of the changes in your vision that come with darkness are obvious. But the last change that I'll describe is one that you'll probably never notice under ordinary circumstances: your eyes see more slowly in dim light than they do in bright light. The photoreceptors of your retina don't respond immediately to a flash of light. The dimmer the light, the longer the delay between the flash and the photoreceptor's response. When you put on a pair of sunglasses, dimming the light that reaches your eyes, you are actually slowing your vision down by a fraction of a second. Practically, this delay doesn't affect your vision, but it can produce a dramatic optical illusion. (See "Slow Sight.")

Exploring Your Night Vision

Human eyes are built for daylight—for sunshine and rainbows and cloudy afternoons. We are diurnal animals—generally awake and active during daylight hours but resting at night. We grow uneasy when the light begins to fade and the visual sense that we trust above all others begins to change.

The limitations of your night vision reflect the history of our kind. The fear of the dark that plagues many a small child echoes the memories of the distant past, when only the light of a bonfire stood between ancestral humans and fierce predators. (See “Cats’ Eyes.”) Our ancient ancestors

huddled together by the fire; we switch on the lights and chase away the night.

Our language reflects our visual prejudices: no one likes to be kept in the dark, a condition that we equate with ignorance and confusion. But darkness offers its own sort of wisdom, its own opportunities to explore and learn. Only by keeping yourself in the dark can you test the limitations of your vision and explore its abilities. Don’t chase back the night; explore it. After a visit to the night world, you may find yourself dazzled by the sun, blinking in the daylight, and eagerly awaiting the return of the darkness, as fear of darkness gives way to fascination for a different world. * * *

Science and Technology

Find That Sound!

Close your eyes and listen to the world around you. Can you identify and locate the sounds that you hear? Are those people talking on your right or left? Is that humming coming from the ceiling fan above you or the air vent at your feet? Maybe the radio is on. Is it near you, or far away?

Open your eyes and confirm the information your ears gave you. How did you do?

Identifying where a sound is coming from is something you do unconsciously all the time. You use this information to help you move safely and efficiently through the world. When a car honks, you know where the sound is coming from; when a friend calls your name, you look in that direction.

When you think about the location of a sound source, you can think about it in three ways: its distance above or below you; its distance to the right or left of you; and its distance near or far

from you. A bird, for example, might be singing five feet to the right of you, ten feet above you, and fifteen feet away. Your ears and brain work together to give you enough information to know all three of these distances fairly accurately, just by listening.

Up or Down: What Do Your Ear Flaps Do?

When a plane flies overhead, it sounds like it's above you. A small dog barking at your feet sounds like it's below you. Your ability to place these sounds is due in large part to the shape of those flaps on the side of your head—your pinnas. All the wonderful little folds and crevices that characterize your pinnas help you localize sound, specifically allowing you to distinguish up from down. (And you thought they were only good for piercing and washing behind.)

Try this simple experiment. All you need is a set of keys and

a friend who is about your height.

Stand five feet apart, facing each other. Ask your friend to close her eyes. When she has closed her eyes, shake the keys above her head, directly in front of her head, and then below her waist. Ask her to identify the location of the keys after each shake. She should be able to identify each location accurately. Mix up the locations and do a few trials to convince yourself of this. Now that you have seen the pinnas do their stuff, ask your friend to carefully fold over the tops of her ears and hold them there gently, but firmly. Don't let your friend actually plug her ears shut. She should keep her pinnas fixed in this position and keep her eyes closed while you repeat the process of shaking the keys in the same three locations. If she is like most of us, her accuracy will decrease. Switch roles and try it for yourself.

Before any sound waves reach

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your eardrums, they bounce off your pinnas. The folds and crevices in each pinna slightly modify and distort the shape of the sound waves. Because the pinnas are not symmetrical and the folds and ridges are irregular, they distort sounds coming from above differently than sounds coming from below. Your brain uses these different distortions to interpret the location of sounds as being above you or below you. Without these subtle distortions, it would be easy to confuse the sounds coming from various heights.

Sound travels in waves: a series of compressions and expansions of the substance the sound is traveling through (air, water, etc.). The wavelength of a sound is the distance from one compression to the next. The higher the pitch of a sound, the shorter the wavelength. The pinna are unable to help in locating a sound unless wavelengths are no larger than the pinna itself. If a sound is too low, the wavelengths will be so large that the pinna will be unable to alter them. That's why jingling keys are a good sound source for the experiment. The wavelengths of the high-sounding jingle are smaller than the pinna.

There are other factors involved in locating sounds vertically. It's easier to locate a

complex sound—one that contains waves of many different lengths (such as a human voice or the sound of a jet engine)—than it is to locate a simple sound. Experiments have shown that it's difficult to locate sounds of only one wavelength, such as the tone of a tuning fork, in the vertical direction. This is no great tragedy, since such sounds are almost nonexistent in nature.

Right and Left: What Time Is It?

It takes only one ear to figure out whether a sound is coming from above you or below you. Prove this to yourself by plugging one of your ears with an ear plug, a wad of tissue, or (gently) with your finger, and repeating the jingling keys experiment. You should be able to distinguish up from down with only one ear. But can you tell left from right? Try this experiment to find out.

Have your friend sit in a chair with her eyes closed. From five to ten feet away, move in a circle around her. Pick random spots on the circle and shake your keys at your friend's ear height. (You will have to move very quietly around the circle so you don't give yourself away.) Each time you shake the keys, ask your friend to point to them. When you are convinced that she can locate the keys, ask her to plug one ear and repeat the process. With one ear plugged, she'll

have a harder time locating those keys.

Your brain has a remarkable ability to keep track of time. I don't mean that your brain always knows what time it is, but that it can distinguish the order of events that occur in rapid succession. This ability makes it possible for you to tell whether a sound is coming from your left or your right.

Imagine a dog barking to your left. The barks will reach your left ear just slightly before they reach your right ear. In cold, dry air, at 0 °C (32 °F), sound travels at 331.45 meters per second. It moves a little faster in warmer air; a little slower in colder air. For ease of calculation (and to keep the poor dog from freezing), I'll use 350 meters per second, the approximate speed of sound at 24 °C (75 °F).

If your head is about the same size as mine—about 20 centimeters (approximately 8 inches) across—the sound of a dog barking directly to your left will hit your left ear .0006 seconds (that's 6/10,000 of a second) before it hits your right ear. That's not very long (the smallest hummingbirds beat their wings twenty times slower than this), but it is long enough for your brain to know which ear heard the sound first.

Every position around your head will have a unique differ-

ence in timing between your two ears. Your brain uses these timing differences to tell you what direction the sound is coming from. The only exceptions are sounds that come from directly in front of you or directly behind you. Since these sound sources are the same distance from your two ears, the sound arrives at both ears at the same time. Fortunately, your pinnas help you distinguish between sounds coming from directly behind you and sounds coming from directly in front of you. Because the pinnas are opened to the front, the sounds that come from behind are distorted very differently from those coming from the front.

Near and Far: Echoes and Volume

Recognizing the distance of a sound source is as straightforward as comparing the time sounds arrive at your two ears. The most important bit of information the brain uses to tell near sounds from far sounds is the loudness of the sound. All

things being equal, near sounds are loud and far sounds are soft. However, all things are rarely equal. Unless a sound is accompanied by other clues, loudness alone does not tell us much about the distance of the sounds' source. If you have a stereo, you probably prove this to yourself all the time without even realizing it. When you turn the volume up or down on the stereo, it does not make it sound closer or farther away, only louder or softer.

Although you are not consciously aware of it, one important bit of information that helps you judge the distance of a sound source is whether echoes accompany an arriving sound or follow it. A sound from a nearby source will come directly to your ear, arriving very quickly after being generated; there will be a slight gap between the sound and its echoes. Sounds that come from far away, however, are accompanied by reflections that bounce off other objects—walls, ceilings, floors, buildings. These reflections give far-away sounds

a sense of space that nearby sounds don't have.

Another important clue to distance is time delay. Far sounds take a little longer to arrive than near sounds. The instruments in the back of an orchestra—the horns and the timpani, for instance—can arrive 20 milliseconds later than the violins in the front row. The differences are subtle, but combined with loudness and echo content, they are more than enough to help give you a perception of the relative distances of sounds.

Because we are constantly locating sounds, most of us take the process for granted. Even as I write this sentence, I can hear a co-worker talking on my right and a phone ringing on my left. Listen again to the sounds all around you. Not only does your ear “hear” these sounds, it also helps you locate them, working with your brain to give you valuable information about the world in which you live.

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