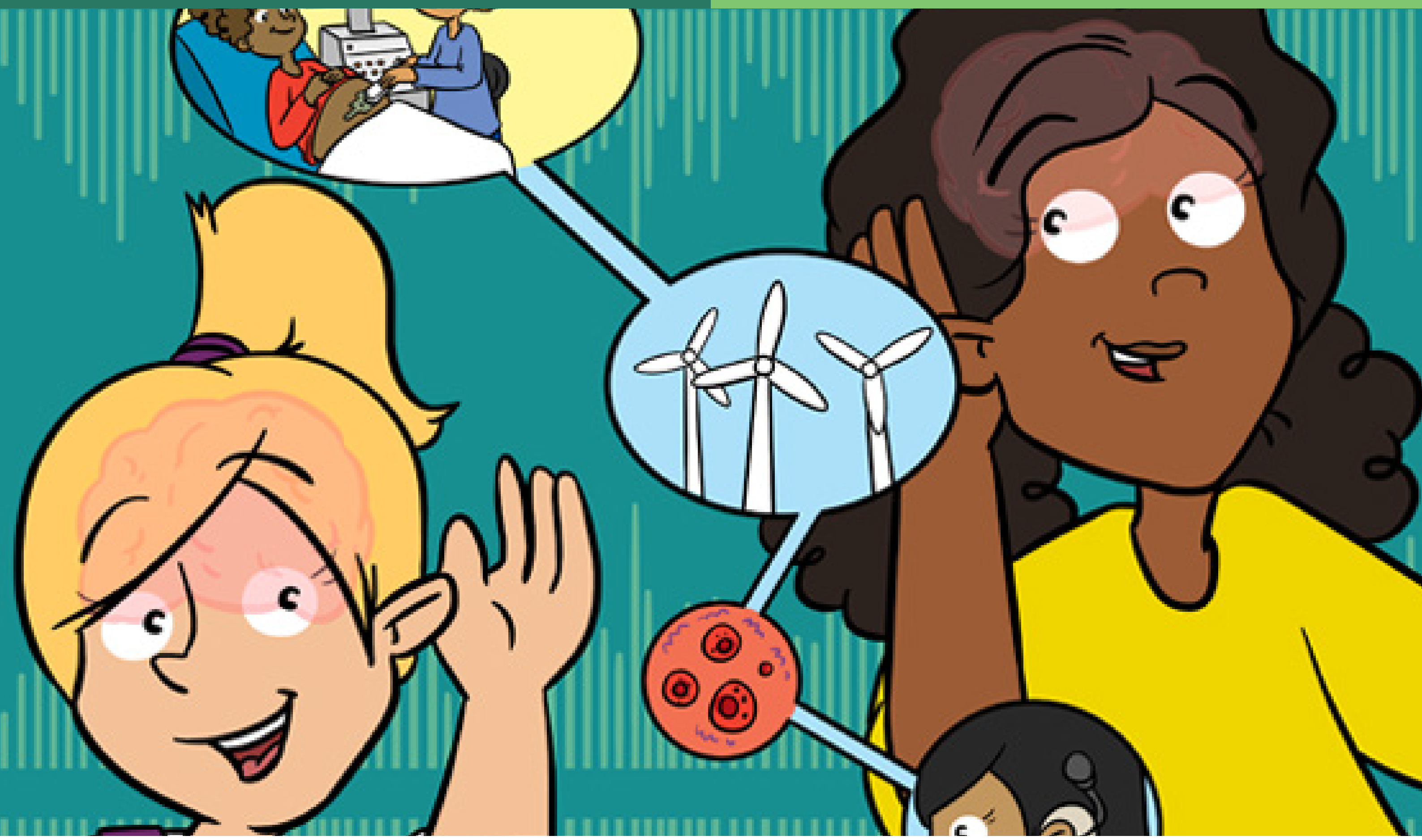
Frontiers | Frontiers for Young Minds

A world of sound

Edited by
Francesco Aletta, Naomi Curati, Gianluca Memoli and Christian J. Sumner



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About Frontiers

Frontiers is more than just an open-access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

About Frontiers for Young Minds

Frontiers for Young Minds believes that the best way to make cutting-edge science discoveries available to younger audiences is to enable young people and scientists to work together to create articles that are both accurate and exciting. That is why distinguished scientists are invited to write about their cutting-edge discoveries in a language that is accessible for young readers, and it is then up to the kids themselves – with the help of a science mentor – to provide feedback and explain to the authors how to best improve the articles before publication. As a result, Frontiers for Young Minds provides a collection of freely available scientific articles by distinguished scientists that are shaped for younger audiences by the input of their own young peers.

What are Frontiers for Young Minds Collections?

A Collection is a series of articles published on a single theme of research and curated by experts in the field. By offering a more comprehensive coverage of perspectives and results around an important subject of research, we hope to provide materials that lead to a higher level of understanding of fundamental science. Frontiers for Young Minds Collections will offer our international community of Young Minds access to the latest and most fundamental research; and, most importantly, empowering kids to have their say in how it reaches their peers and the wider public. Every article is peer reviewed according to the Frontiers for Young Minds principles. Find out more on how to host your own Frontiers for Young Minds Collection or contribute to one as an author by contacting the Frontiers Editorial Office: kids@frontiersin.org

A world of sound

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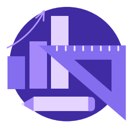

Mathematics and Economics

About this collection

Everything vibrates and makes sound, from the smallest living cells in the human body to the biggest skyscrapers. Sound itself is a travelling wave of vibrating particles but, amazingly, our brains can understand sounds – gathering information and meaning from these vibrations. Sounds are the building blocks for language, and culture, and can be a source of both pleasure and pain. In the modern world sound is also fantastic tool for medicine, industry and monitoring the natural environment. But it can also be polluting and bad for our health. For many animals, sound is essential for survival, enabling them to communicate, hunt and navigate their world.

Hearing loss affects around 5% of the world's population, and encouraged by the WHO, scientists across the world are working to find new ways to improve deaf people's lives. The science of sound cuts across many disciplines - from medicine and neuroscience to the environment - and people who study sound use complex mathematics and cutting-edge technology to help us understand how sound affects us and our planet.

2020/21 was the first International Year of Sound, initiated by the International Commission for Acoustics, in response to UNESCO resolution 39C/49, as a celebration of sound and how it enters our lives in so many ways.

To celebrate the year of sound, here you will find a collection of articles written by experts from the UK Acoustics Network and the International Year of Sound team. These articles explore the fascinating world of sound and how it benefits and causes problems to people, other animals, and our environment.

Editorial consultant: Caryl Hart, Children's Author.

acoustics.ac.uk
THE UK ACOUSTICS NETWORK

About the editors

Francesco Aletta
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Francesco Aletta is an architect and urban sound planner by training, and a lecturer at University College London (UK). He has been active in soundscape studies for more than 10 years, with an interest in methods for measuring soundscape perception by people and standardization processes, as well as how to translate soundscape descriptors in languages other than English.

Naomi Curati
University of Manchester

I work at the University of Manchester helping academic researchers, businesses, and other organizations apply for funding for collaborative projects that create benefits from research outputs. I did a PhD in Chemistry, researching how molecules interact with light; and a master's degree in Museum Studies. Since then I have worked in different fields, including science museums and the nanotechnology industry. Before my current job I was Public Engagement Manager for the Mathematics of Waves and Materials research group at the University of Manchester, helping mathematicians explain their work.

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Gianluca has been working with sound since 2004, both in industry and in academia. A physicist, an engineer and–according to his two children–an inventor, Gianluca is passionate about amateur dramatics. He received the UK prize for Communicating Acoustics to the Public in 2013, after talking about his research to more than 66,000 people.

Christian J. Sumner
Nottingham Trent University

Chris Sumner is an Associate Professor in Auditory Neuroscience at the Nottingham Trent University. He has a background in computer science, and so views the brain as a big computer—and wants to understand the program for how we hear! He has wide interests across hearing, from how the brain separates out simultaneous sounds (such as instruments in an orchestra) or how single brain cells process sound, to how hearing changes as we age. His career choice stemmed from an interest in music, and he lacked most of the necessary characteristics to become a rock star.

Caryl Hart
Independent Children's Author

Caryl Hart is an award-winning children's author who writes picture books and young fiction. She runs creative literacy workshops for schools, libraries, communities, and festivals. Her books have won and been shortlisted for many regional and national awards. Meet the Oceans was one of Waterstones Best Books for Babies & Toddlers 2021 and Books for Topics' Best EYFS Curriculum Support 2021. Girls Can Do Anything was shortlisted for the Independent Bookshop Week Book Award, 2019, and The Girl who Planted Trees won Teach Early Years Best Picture Book Award, 2022 and was chosen as one of the best books of 2022 by the UK Children's Laureate, Joseph Coelho. Her best-selling Princess series and Albie series have each sold over a quarter of a million copies and her books are published in numerous languages all over the world. Caryl lives in Sheeld with her family and loves walking in the hills, cycling, and wild swimming. For more information, visit www.carylhart.com or send Caryl a message on Twitter @carylhart1 or Instagram @carylhart. She would love to hear from you!

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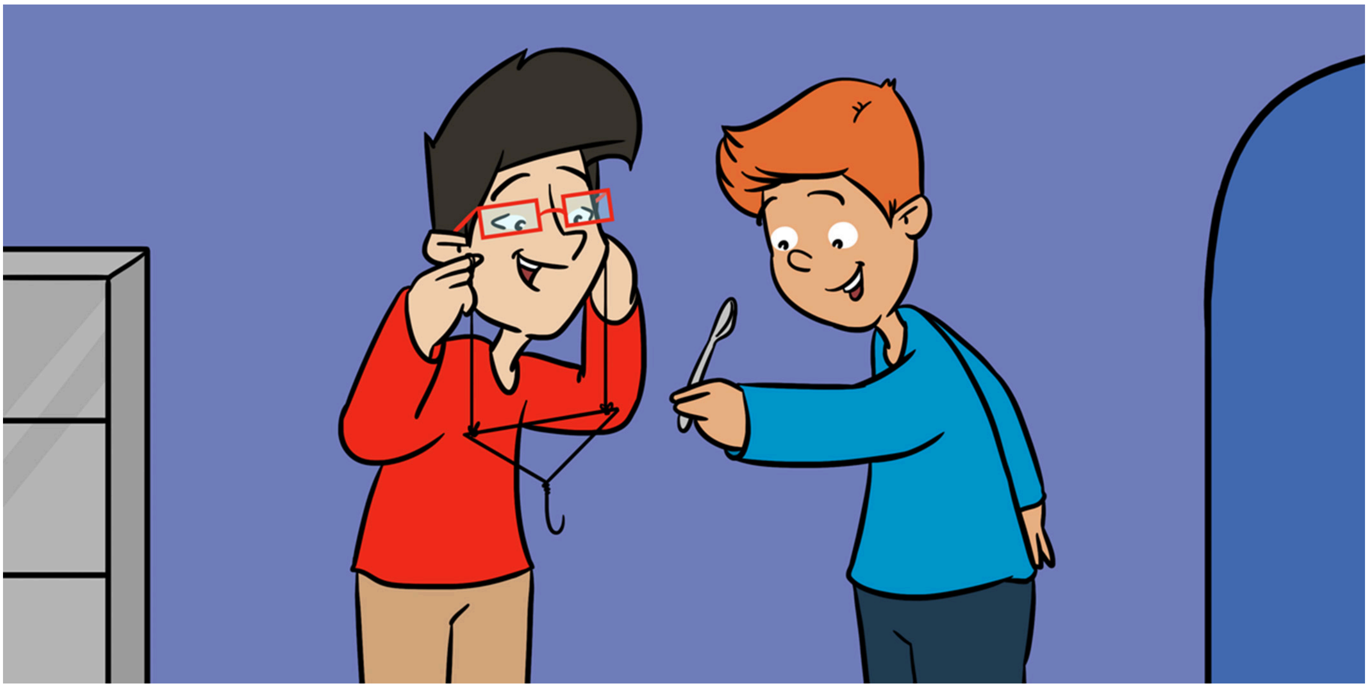

HOW LONG IS A NOTE? SIMPLE EXPERIMENTS TO UNDERSTAND SOUND

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YOUNG REVIEWERS:

PORYA
AGE: 15

YOUNG TALENTS!
AGE: 13

What is sound? How does it move? What exactly are the characteristics of sound, like amplitude and pitch? In this introduction to the World of Sound, we present several simple experiments you can do at home, that can help young readers like yourself to find the answers. Find a coat hanger, a slinky, a flowerpot, and your favorite grown-up assistant...and get started!

SOUND IS ALL AROUND!

Sound is all around us. From the crunching of leaves underfoot on an autumn walk, to the click-clack of a keyboard when we type, we make sounds just by being alive! Often, sounds are useful: we use our voices to communicate, make music, and laugh. An alarm alerts us to danger, and we listen for traffic when crossing the road. But sounds can be unhelpful, too: noise can damage our hearing and disrupt our sleep. Understanding sound can help scientists and engineers make use of the good aspects of sound and minimize the bad. In this article, we will conduct some fun experiments that explore the concept of sound. We will discover what sound really is, find out how it travels, and learn what makes one sound different from another. We will do all of this using everyday objects! So, grab your adult helper and we can get started!

WHAT IS SOUND?

You may have heard that sound is a vibration, but what exactly does that mean? Gently put two fingers on your throat and hum loudly. Can you feel movement? That is your voice box vibrating! But how does the sound get from your vibrating voice box to a listener's ears?

When you hum, speak, or sing, you are actually forcing air through your voice box. This causes the insides of your voice box to vibrate. These vibrations cause the skin, tissues, and air inside your breathing tubes to vibrate too, and the sound spreads like the ripples on a lake. If you are speaking or singing, the vibrating air comes out through your open mouth—and, if you are humming, probably from your nose—but in both cases, the vibrating skin of your throat causes air molecules touching the skin to vibrate, too (see also below). These vibrations spread outward from your body, through everything around you.

Eventually, some of these vibrations will reach someone's ears. They then travel down long tubes in each ear, called the ear canal, and hit the listener's ear drums—thin pieces of skin stretched over the ends of the ear canals. The ear drums also start to vibrate, and this sends signals to the listener's brain, which then recognizes these vibrations as sound.

SOUND TRAVELS IN WAVES

Although sound needs a substance like air to travel through, the air itself does not travel—it is the vibrational *movement* that travels from molecule to molecule. We call this a sound wave.

Try this:

1. *Hold a slinky on a flat surface like a table top, with one end in each hand.*
2. *Pull your hands as far apart as you can, so the slinky is stretched.*
3. *Now, move your right hand back and forth toward the left, keeping your left hand still.*

What happened? If you watched carefully, you probably saw the slinky coils bunch up, and it probably looked like the bunch of coils was moving toward your left hand. The coils of the slinky are like the air molecules in a sound wave. They first bunch together (this is called a **compression**), and then move apart (this is called a **rarefaction**). It might look like the bunched-up coils are traveling along the slinky, but if you mark one coil with a piece of sticky tape, you will see that the bunched coils are actually moving back and forth around a fixed point. Another way to show how waves travel is a jelly-bean wave machine, here demonstrated by the UK National STEM Centre.

COMPRESSION

The part of a wave in which the molecules are closest together.

RAREFACTION

The part of a wave in which the particles are farthest apart.

CROWDS OF MOLECULES

Now let us look at the movement of sound in terms of molecules. You know that substances like air, water, wood, and stone are made up of trillions of miniscule particles called molecules. Molecules in solids are closer together than molecules in the air. All these molecules crowded together behave like a crowd of people. Imagine you are in the middle of that crowd, jostling for space with the people around you. If you try to move, you will probably push against the other people around you, causing them to move too. The tighter the crowd, the more one person's movement affects the others.

Sounds travels through substances in a similar way. Because the molecules in liquids and solids are closer together than those in the air, sound moves faster through these substances than it does through the air. In fact, sound travels through the air at about 340 meters per second, whereas it travels through water at close to 1,500 meters per second. That is the same as running almost four times around a running track in just ONE SECOND! Let us try another experiment to learn more (Figure 1).

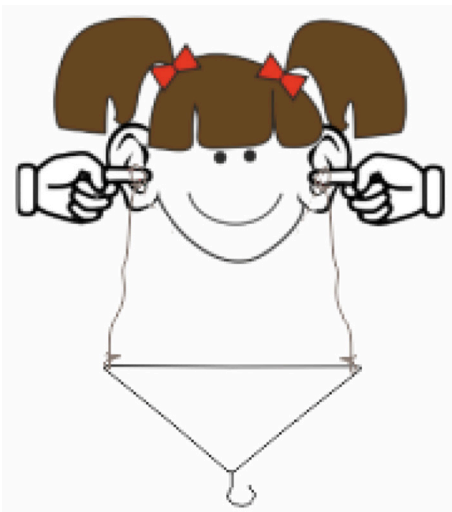

Figure 1

Figure 1

Two strings and a coat hanger to demonstrate the different sound speed in air and in solids. When you put the fingers in your ears, sound reaches you through the strings. When the fingers rest to the side of the head, the sound reaches your ear drum passing through air, where sound is slower.

Try this:

1. *You will need wire coat hanger and two pieces of string, each around 20 cm long.*
2. *Tie a small loop at one end of each piece of string, big enough for your finger to fit inside.*
3. *Tie the other ends of each piece of string to the corners of the coat hanger.*
4. *Put your index fingers through the loops and allow the coat hanger to dangle upside down away from your body.*
5. *Ask a friend to gently hit the coat hanger with a spoon or fork. What do you hear?*
6. *Now, with the coat hanger still dangling from the strings around your fingers, bring your fingers to rest on the sides of your head near (but not in) your ears. You will need to bend forwards a bit so that the coat hanger can dangle freely.*
7. *Ask your friend to hit the coat hanger again. What do you hear now?*

In this classical experiment, which you can see repeated by Science Ireland here, your friend should hear the same sound no matter where your fingers are, but you might hear something different in the two cases. This has to do with how the sound reaches your ears in each case and, in particular, with the different speed of sound in air and in solids. When your fingers are touching your head next to your ears, the sound reaches your ear drum through the strings, at a faster speed. When your fingers are not touching your face, the sound reaches you through the air: not only it is slower, but energy is lost all around, so it sounds less loud. This is also why, in spaghetti-western movies, the hero can always hear an approaching train better by putting their ear on the rail tracks (do not do THIS at home!). A similar method is used by rail engineers (with a microphone attached to the track) for safety tests: if there is a fault along the track, the sound of approaching trains gets distorted.

A SOUND WAVE IN DETAIL

We have learned that sound moves through a substance in waves, which consist of bunchings-up called compressions and stretchings-out called rarefactions. The movement of sound waves is tricky to draw, but we can make a graph to plot the pressure in a sound wave at a fixed instant in time (Figure 2), using a shape repeated over distance. Pressure is highest in a compression and lowest in a rarefaction, so our plot has alternating crests (peaks) and valleys (troughs). A single wave consists of one peak and one trough on our pressure plot.

Figure 2

This figure represents what could be measured, at a fixed moment in time, when a single note is played (e.g., with a tuning fork). The tuning fork generates a pressure wave that travels at the speed of sound, causing a series of compressions and rarefactions of molecules. The pressure is highest in a compression, when the molecules are closer together, and lowest in a rarefaction, when they are mostly separated. The wave is represented by a repeated shape, whose height is the amplitude of the wave, measured in units of pressure (Pascal). The wavelength (measured in meters) is the distance needed for a point in the structure to repeat itself e.g., the distance between two peaks.

AMPLITUDE

The height of a wave, measured from its position to the top of a peak or the bottom of a trough.

WAVELENGTH

The length of a wave, obtained at a fixed instant in time by measuring the distance between a point on a wave and its next repetition.

FREQUENCY

The number of waves that pass a fixed point in 1 s. Measured in hertz (Hz).

VOLUME

In this article, we defined "volume" the amplitude of a sound wave expressed in decibel.

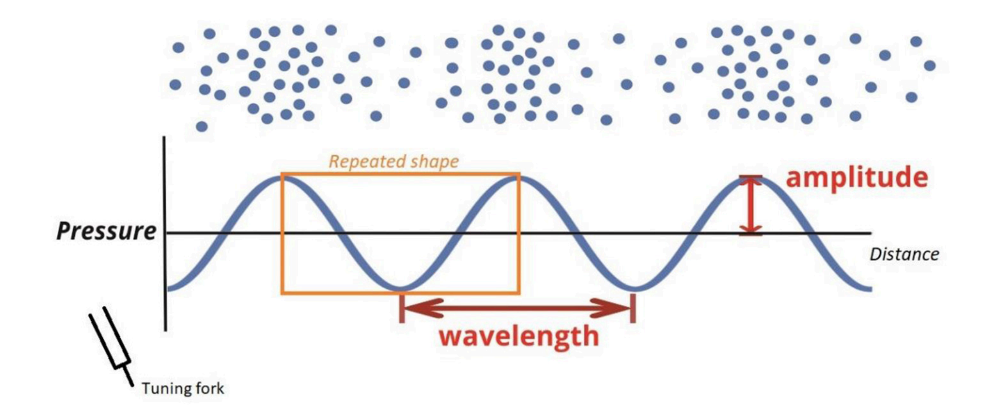

Figure 2

In Figure 2, the **amplitude** and the wavelength are marked—these are key features of sound waves. The amplitude is the height of the wave, measured from the top of a peak or the bottom of a trough. The **wavelength** is the length in meters from a fixed point on one repetition of the shape (e.g., its peak) to the same point on the next repetition.

Sound has another feature that does not show up on our plot—**frequency**. Frequency means "how often" and, in a fixed listening position, the frequency of a musical note tells us how many vibrations happen every second when that note is played. Frequency is measured in hertz (Hz) and, in the case of a single note (i.e., a single frequency, like in Figure 2), frequency and wavelength are related: waves with long wavelengths have low frequencies, and those with shorter wavelengths have higher frequencies.

Wavelengths for sound can be very large. As an example, the note usually used for tuning forks (440 Hz) has a wavelength on 78 cm (in air).

In general, however, a sound contains multiple frequencies (think about playing different notes simultaneously on a piano) and these determine the shape that repeats over distance in Figure 2. The frequencies in a sound often depend on how the sound is generated: using the same hammer to hit two bells of different size, for instance, may produce two very different frequencies.

AMPLITUDE: HOW LOUD IS A SOUND?

One of the things that makes one sound different from another is the loudness, or **volume**, of the sound. If the volume of a movie is too low, you might not be able to hear what the characters are saying. If the music in your earbuds is too loud (at a high volume), it could damage your hearing!

The amplitude on our pressure graph tells us how loud the sound is. Loud sounds have strong vibrations, with high-pressure compressions and low-pressure rarefactions, so the greater the amplitude, the higher the volume and the louder the sound. Loudness is measured in **decibels** (dB). The decibel scale is logarithmic, which means it increases by multiplication rather than by addition. An increase of 10 dB means the sound is ten times as loud. But an increase of 20 dB is $10 \times 10 = 100$ times as loud. A 30-dB increase is $10 \times 10 \times 10 = 1{,}000$ times louder. A whisper measures about 15 dB, normal talking about 60 dB, and a baby crying can reach as high as 110 dB! Sounds at 110 dB or more feel uncomfortably loud, and noises above about 130 dB are actually painful.

DECIBELS

Decibels are a relative scale for amplitude, so the volume measures how many times the amplitude of a pressure wave is bigger than a reference pressure (For sounds traveling in air, this reference is 0.00002 Pascal (20 micro Pascal), which is the minimum pressure humans can hear a note at 1,000 Hz).

Try this:

1. *You will need a metal slinky, some tape and a plastic flowerpot.*
2. *Hold a metal slinky at one end and let it hang to the floor.*
3. *Lift a few coils so that they bunch together, then release them. What sound does it make?*
4. *Tape the top of the slinky to the bottom of the plastic flowerpot (the opening of the flowerpot should face away from the slinky, as in Figure 3).*
5. *Hold the flowerpot so that the slinky hangs down to the floor.*
6. *Lift and release the coils as before. The noise made by the slinky alone is tinny and quiet, but with the flowerpot attached, it should be surprisingly loud!*

Figure 3

Figure 3

This experiment uses a slinky and a flowers pot to show how a container can increase the amplitude of a sound wave. First, the experimenter holds one end of the slinky and lets the other end fall. The sound produced in this way is very low in amplitude. Then, a flowers pot is attached to one end of the slinky (using tape), the experimenter holds the flowers pot and lets the other end of the slinky fall. The resulting sound, in this second case, is similar to a Star Wars laser blast (https://www.youtube.com/watch?v=3_JdIrQGKXc).

Why does this happen? On its own, the slinky has only a small vibrating surface acting on the air around it. The flowerpot, on the other hand, has a larger surface area and a large volume of air inside. When the two are attached together, the vibrations in the slinky make the flowerpot—and the air inside and outside it—vibrate. These vibrations build up and make the sound louder. We say the flowerpot amplifies the sound (makes it louder). You can do a similar experiment with your phone. Set it to play some music. Then, place it inside a dry mug to have the sound amplified.

In both cases, the size of the container determines which frequencies are amplified, and this could be used advantageously e.g., in metamaterials [1]. According to the ancient roman architect Vitruvius, for instance, small jars made of metal could be used in theaters to increase the volume of people singing: a theory that, according to some scientists, influenced the building of multiple European churches during the Middle Ages.

PITCH: HOW HIGH OR LOW IS A SOUND?

How high or low a noise sounds is called **pitch**. Pitch is related to the way a human perceives a sound's frequency but related to how humans can hear it. Humans can hear frequencies between about 20 Hz (a low-pitched rumble, like thunder) and 20,000 Hz (a high-pitched whistle). In the standard way of tuning musical instruments, "middle C" (or C4) corresponds to 256 Hz, while the note A "above middle C" corresponds to the tone of a tuning fork (440 Hz). In music, going up one octave in pitch means doubling the frequency of the note. Interestingly, when we play two musical notes at the same time, those with frequencies in simple ratios (such as 20, 22, and 24 Hz) tend to sound more pleasing than combinations of notes with complex frequency ratios (such as 20, 21.5, and 37 Hz).

PITCH

According to Britannica, it is "the position of a single sound in the complete range of sounds". It is a quantity related to the frequency of a sound, but on a relative scale.

Many other animals can hear frequencies that humans cannot hear. Frequencies higher than humans can hear are called **ultrasound**, and those lower than our hearing-range are called **infrasound**. Echo-locating bats and dolphins use ultrasound to work out where objects are, and elephants use infrasound to communicate over long distances [2, 3].

ULTRASOUND

Sounds at frequencies too high for humans to hear them. This means typically above 20,000 Hz. Animals like bats use ultrasound to fly and hunt.

INFRASOUND

Sound sat frequencies too low for humans to hear them. Typically this means below 20 Hz. Infrasounds are created by very large objects, like wind turbines.

Try this:

1. *You will need a balloon and a metal nut (the kind that screws onto a metal bolt).*
2. *Place the nut inside the balloon.*
3. *Blow up the balloon and tie a knot in the end.*
4. *Hold the balloon near the knot and swirl it around so that the nut inside moves in circles.*

You should hear a loud whirring noise as the edges and corners of the nut bounce off the inner surface of the balloon. This is because the nut is making the balloon vibrate and generating sound. Experiment by swirling the balloon at different speeds. What happens to the pitch of the sound as you alter the speed of the movement?

The pitch varies because the speed at which the nut is rotated affects the frequency of the sound produced. Higher speeds correspond to higher frequencies: if the number of rotations of the nut in a second doubles, the corresponding sound has increased in frequency by one octave. The size of the balloon is also important: for the same swirling movement, the velocity with which the nut rotates changes with the size of the balloon.

WHO STUDIES SOUND?

The study of sound is called **acoustics**, and the scientists and engineers who work on sound are called acousticians. Acousticians come from different specialties including biology, engineering, music, mathematics, physics, and psychology. They work on many aspects of sound, from environmental noise control, to understanding speech and language development. Others even study how to use sound waves to check the health of a baby before it is born. The one thing acousticians have in common is a fascination with sound. We hope you share this fascination and enjoy these noisy at-home experiments. Maybe you will inspire a future acoustician or even become one yourself!

ACOUSTICS

According to Britannica, it is "the science concerned with the production, control, transmission, reception, and effects of sound". Acoustics covers also frequencies beyond the range humans can hear.

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

PORYA, AGE: 15

I love mathematics, physics, chemistry, and biology. I like the piano and I also play the piano.

YOUNG TALENTS!, AGE: 13

We are Apurva, Kalyani, Akshada, Vedan, Manvi, Parth, Krishna, Ajay, Nikhil, and Hindavi. We all live in hostels of our school and love to cook Maggie when we are not caught by our wardens. We are Navodayans and love to have fun in classes. Our favorite pass time is teasing each other and reading science books.

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I work at the University of Manchester helping academic researchers, businesses, and other organizations apply for funding for collaborative projects that create benefits from research outputs. I did a PhD in Chemistry, researching how molecules interact with light; and a master's degree in Museum Studies. Since then I have worked in different fields, including science museums and the nanotechnology industry. Before my current job I was Public Engagement Manager for the Mathematics of Waves and Materials research group at the University of Manchester, helping mathematicians explain their work.

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Caryl Hart is an award-winning children's author who writes picture books and young fiction. She runs creative literacy workshops for schools, libraries, communities, and festivals. Her books have won and been shortlisted for many regional and national awards. *Meet the Oceans* was one of Waterstones Best Books for Babies & Toddlers 2021 and Books for Topics' Best EYFS Curriculum Support 2021. *Girls Can Do Anything* was shortlisted for the Independent Bookshop Week Book Award, 2019, and *The Girl who Planted Trees* won Teach Early Years Best Picture Book Award, 2022 and was chosen as one of the best books of 2022 by the UK Children's Laureate, Joseph Coelho. Her best-selling *Princess* series and *Albie* series have each sold over a quarter of a million copies and her books are published in numerous languages all over the world. Caryl lives in Sheffield with her family and loves walking in the hills, cycling, and wild swimming. For more information, visit www.carylhart.com or send Caryl a message on Twitter @carylhart1 or Instagram @carylhart. She would love to hear from you!

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Gianluca has been working with sound since 2004, both in industry and in academia. A physicist, an engineer and–according to his two children–an inventor, Gianluca is passionate about amateur dramatics. He received the UK prize for Communicating Acoustics to the Public in 2013, after talking about his research to more than 66,000 people. *g.memoli@sussex.ac.uk

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WHAT HAPPENS WHEN WE HEAR?

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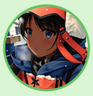
YOUNG REVIEWERS:


ANJALI
AGE: 12


DECLAN
AGE: 14


GONZALO
AGE: 13


GREY
AGE: 14


JUAN
AGE: 14

What happens when we hear? Where does the sound go when it enters our ears? Our ears sense the vibrations of the air and convert them into electrical signals the brain can process. But that is only the start. The brain uses tens of thousands of nerve cells to hear even the quietest or simplest sound. With those nerve cells, the brain is solving a never-ending puzzle: figuring out what is going on in the world. To do that, the brain must separate out sounds that are occurring at the same time, recognize them, and describe them in lots of ways, such as how loud a sound is and where it is coming from. This article gives an overview of how the ears and brain work together, so we can live in a world of sound.

THE WORLD OF SOUND

Imagine you are sitting by a very still lake. Now imagine you place two small toy boats on the water's edge, about a meter apart, like the boy in the picture above. You throw a stone into the water, farther out than the boats. When the stone hits the water, it creates ripples that move outward in a circle from where the stone sank. When the waves reach your boats, the boats bob up and down. If your stone landed an equal distance from each boat, both boats will start moving at the same time. But if your stone was closer to the left boat, it will start to bob around before the boat on the right.

Now imagine the lake is busy. A dog splashes nearby, a jet ski whizzes past in the distance, and ducks swim around. Each moving thing creates more waves of various sizes, coming from lots of directions—and each wave will move your boats in a specific way.

What if you could not see the entire lake, but could only see the two boats? You might know that *something* is creating ripples, but it would be difficult to work out what was causing them. This is exactly what you do when you listen to sounds. When people talk, birds sing, or cars go by, they create invisible ripples of air that spread outwards like the ripples on the lake. When those ripples reach your ears, they cause moving parts inside your ears to "bob" about, just like those toy boats, and nerves inside your ears send signals about this bobbing motion to your brain. Your brain then works out what those sounds are and where they are coming from—even if you cannot see what is making the sound! Hearing can create a vivid picture of the world around you, and most of the time you do not even notice you are doing it! Scientists are still figuring out how this happens [1].

WHAT HAPPENS INSIDE YOUR EARS?

If you could see air move in slow motion, you could watch sound vibrations travel from someone's hands when they clap, through the air, to your ears. Of course air is invisible, and it vibrates much too fast for our eyes to follow, but some scientists have devised a clever way for you to see the sound waves. To learn more about the physics of sound in the air, read this Frontiers for Young Minds article.

Your ears are made up of several parts (Figure 1). The flappy bits on the sides of your head are called your outer ears. The outer ear collects the sound waves traveling through the air and funnels them into the **ear canal**, where they bounce against a thin piece of skin about 8 mm across (a little smaller than an M&M candy), called the **eardrum**, which is stretched across the end of the ear canal. Your eardrum vibrates to the sound waves that hit it. Attached to the other side of the eardrum are three tiny bones—the tiniest bones in your body. They pick up the vibrations from the eardrum, and send them into the inner ear, or **cochlea**. The cochlea is a spiral tube filled with salty liquid that moves rapidly back and forth based on the vibrations of the air.

EAR CANAL

A tube that carries the sound to the ear drum.

EARDRUM

A skin-like membrane that vibrates in response to sound, converting the vibrations in the air to motion of the middle ear bones.

COCHLEA

A spiral chamber, made of bone and filled with fluid, that moves in time with the middle-ear bones and ear drum. In turn, this moves the basilar membrane.

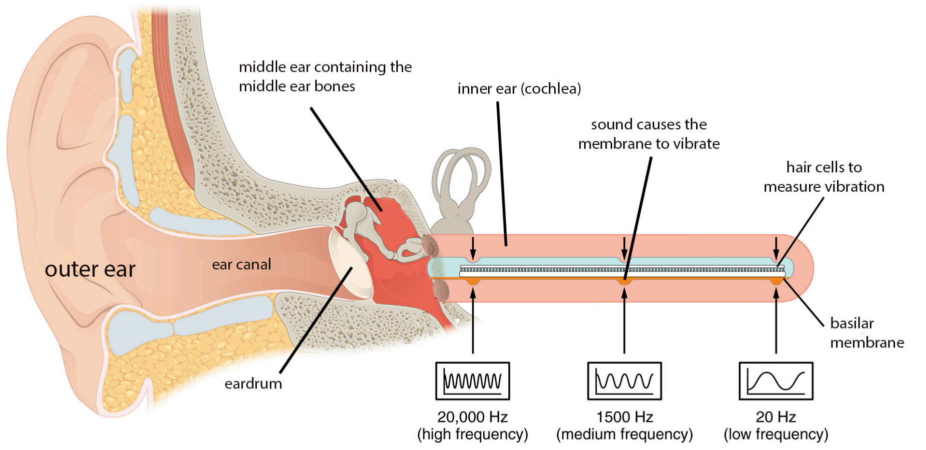


Figure 1

Figure 1

The parts of the outer, middle, and inner ear are shown. In the inner ear, the cochlea is cut away to show the basilar membrane. The inner ear is also shown as straight, so you can see how the membrane works to separate high- and low-frequency sounds, which are measured in Hertz (Hz). In reality, the cochlea is coiled up inside the skull (see Figure 2).

BASILAR MEMBRANE

A flexible membrane in the inner ear that moves in time with the movement of the surrounding fluid. The part that moves most depends on the frequency of the sound.

FREQUENCY

The rate of vibration of sound waves in the air. The number of times per second that air molecules complete a cycle of being squashed together, expand out, and back.

HAIR CELLS

Cells on the basilar membrane that convert movement into electrical signals, which are sent to the brain via nerves. They have tiny hairs that move around with the fluid.

AUDITORY NUCLEI

A collection of brain cells close together in the brain that are dedicated to processing sound. The medial superior olive and auditory cortex are examples of auditory nuclei.

The cochlea is divided into two sections by a skin-like layer called the **basilar membrane**. Sound vibrations entering the ear cause this membrane to vibrate up and down. The membrane closest to the outer ear is more sensitive to high-**frequency** sounds—as high as 20,000 vibrations per second or Hertz (Hz). If you are not sure what frequency is, you can read more about it here. This is far higher than even the highest musical notes, like those made by a piccolo or a whistle, which can be as high as 4,000 Hz. Generally, only young people can hear this well: most older adults aged around 60 can only hear up to about 10,000 Hz. The other end of the basilar membrane vibrates most to low-frequency sounds such as those made by a double bass, which can be as low as 40 Hz—close to the lowest we can hear (20 Hz). Speech falls mostly in the middle range of frequencies, from 100 to 2,000 Hz. So, the cochlea "sorts" sounds according to frequency. This helps us to know what frequency a sound is (e.g., what musical notes) but also to separate out sounds of different frequencies which occur at the same time!

All along the basilar membrane are tiny **hair cells** that measure these vibrations and turn them into electrical signals. Each cell is connected to a nerve fiber, which carries the electrical signals to the brain. The brain then decodes, or interprets, these signals and works out what the sound is and where it is coming from. Of course, there is still much more to how the ear works. You can find out more in other Frontiers for Young Minds articles here, or here.

YOU HEAR WITH YOUR BRAIN

Your brain is like a very powerful supercomputer! It is your brain's job to make sense of the electrical signals sent from your ears. The parts of the brain that process sounds are called **auditory nuclei** (Figure 2). Within the auditory nuclei, brain cells sense specific types of sounds. Some brain cells like low-frequency sounds, such as car engines, and others like high-frequency sounds, such as birdsong. The brain cells that like low-frequency sounds often cluster together, and those that like high-frequencies do the same. We say they are arranged into a "map" of frequency, which helps you to know what frequency of sound you are hearing.

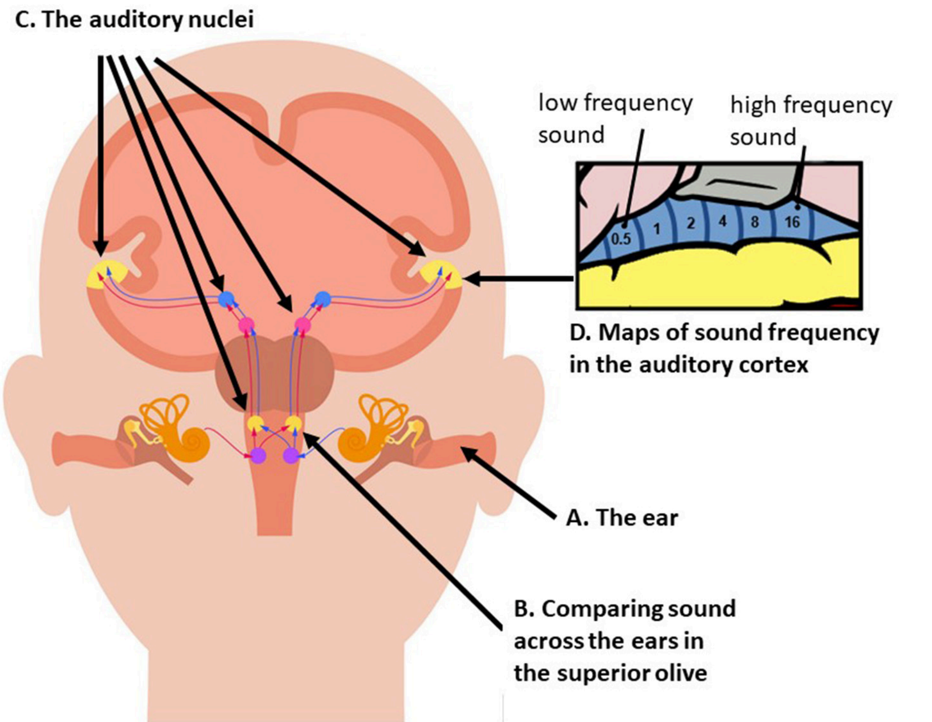


Figure 2

Figure 2

(A) The ear, where sound enters. **(B)** The "superior olive" where sound from the two ears is compared. **(C)** Other auditory nuclei. Information about sound passes through these, and each nucleus has a different job to do, processing the sound so we can understand it. Scientists are still figuring this out. **(D)** The close-up shows a frequency map in the auditory cortex, another part of the brain important for processing sound. In the close-up the upper layer of the brain has been lifted back to reveal the map (Image credit: Modified from Wikipedia Commons).

Some auditory nuclei have extra special jobs that no other parts of the brain can perform. One nucleus, called the **medial superior olive**, compares the times that a sound arrives at each ear [2]. Just like our example of the toy boats on the lake, sounds from the left will arrive at the left ear first and will take a little longer to arrive at the right ear. If the sound comes from in front, it will arrive at both ears at the same time. This is one of the ways that your brain can work out where the sound is coming from (for more see this Frontiers for Young Minds article).

MEDIAL SUPERIOR OLIVE

A nucleus of the brain that is dedicated to processing information about sound and is important for knowing where sounds come from.

The brain does lots of other jobs to help you understand the sounds around you. For example, it can work out how loud a sound is, or spot new and unexpected sounds. It can recognize words, and can work out how an object is moving from the changes in sound waves over time. Imagine almost any aspect of sound or how it can change, and you can probably find brain cells that can measure it!

MAKING SENSE OF SOUNDS

The job of the brain is to turn sounds into information about the world around us that makes sense. For example, when you hear a person talking and understand the words they say, you are not just working out whether the sounds are loud, quiet, close, distant, still, or moving. Your brain is also trying to identify the sounds. It does this by drawing on all the knowledge it already has about those sounds (Figure 3A). We understand words because we have already learned the language and know what many words sound like; so you hear not just sounds, but words that have meaning to you. So, how we understand sounds is partly dependent on what we already know! Even the things you see can affect the way you perceive sound. This is extremely important when you are listening to someone talking—seeing a person's face makes them easier to understand (see this Frontiers for Young Minds article for more about how what we see affects our hearing).

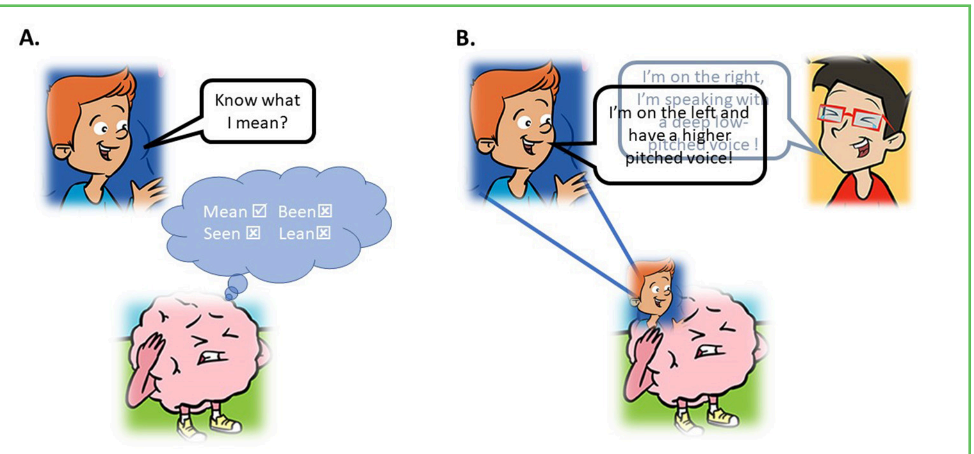


Figure 3

Figure 3

(A) What you know about sounds affects what you hear and helps you to understand. **(B)** How you listen affects what you hear and helps you separate and understand sounds (Figures adapted from here, here and here).

UNTANGLING ALL THE SOUNDS YOU HEAR

Perhaps the most amazing thing about hearing is how well it works when there are lots of sounds happening at once. Imagine you are with two friends, and they are talking at the same time. You can usually pick out one of the voices to listen to, and not get both friends' words mixed up. The brain uses "tricks" to separate out sounds. For example, if your friends are sitting in separate places, your brain can work out where each voice is coming from by using your medial superior olives! You do not need to think about where the voices are coming from—your brain is wired to do this automatically. *Choosing* which of your friends to listen to is not automatic, and *how* you listen also helps your brain to separate out the voices (Figure 3B). Amazingly, if you *pay attention* to one of the voices, your brain responds more strongly to that voice and you hear it more clearly [3]! For more information, see this Frontiers for Young Minds article.

HEARING: A LOT MORE THAN MEETS THE EAR!

By now, you probably agree that there is a lot more to hearing than just your ears. Your ears convert sounds into signals your brain can deal with. That is not an easy job! But by the time you make sense of those sounds, they have passed through many thousands of brain cells. Your brain and the cells in it work hard to help you make sense of sounds and the information that sounds are telling you about the world. Understanding how we hear is critical to treating hearing problems effectively, which become worse with age. This understanding has also led to technologies such as mp3 files and innovations in artificial speech recognition by computers. If you want to learn more about the exciting world of sound and how we hear it, be sure to check out the other articles in this Collection.

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Anjali likes dogs, mushrooms, and drawing. They do not like mayonnaise and distrust armadillos.

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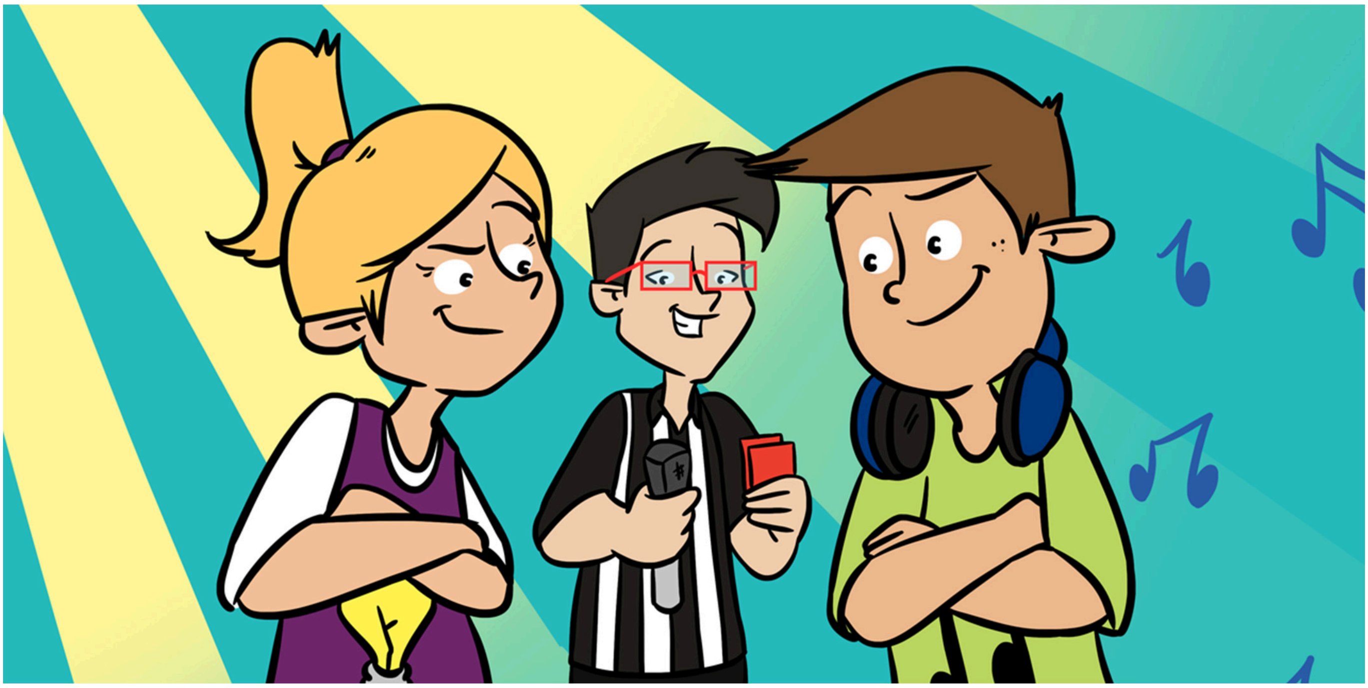

THE LIGHT AND SOUND QUIZ SHOW

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YOUNG REVIEWERS:


GINNY
AGE: 13


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The science of light manipulation started with the ancient Greeks, so we have had many years to develop it. Lenses and holograms are part of our everyday lives. Light and sound are very similar: they are both waves, and they both have particles associated with them. So, why do we not have lenses or displays for sound? Or do we? This article will tell the story of how sound technology is catching up with light technology. We will tell you about acoustic metamaterials, an emerging technology that is quickly becoming part of our loudspeakers, our shows, our cars, our public spaces, and our hospitals—all the places where we want control over sound and noise. The future of shaping and designing sound is in the making! Maybe someday, sound experts will even teach something to light experts!

Imagine being in the audience at a TV studio, waiting for a quiz show to start. There are two teams of three people each, sitting at desks facing each other, with a referee in between them. On the left side is "Team Light," wearing t-shirts with an image of a lightbulb. On the right is "Team Sound," wearing DJ hats and t-shirts with musical notes. The referee introduces the rules: teams score points by telling the audience about things that make their topic special.

ROUND 1: INTERFERENCE AND DIFFRACTION

Team Light is the first to hit the buzzer. "Light is a wave!" shouts their captain. Looking around proudly, the captain adds, "This means we can experience interference or diffraction."

"Correct!" says the referee, giving Team Light a point. She then asks, "Could you please explain what those words mean?"

Team Light replies, "Light travels as a wave, with high peaks and low troughs just like waves on the ocean. **Wavelength** is the distance between one peak in the wave and the next. **Interference** happens when two waves meet in the same space and affect each other. A scientist named Thomas Young demonstrated this really well in a famous experiment called the "**two slit experiment**". He showed that when the peaks of two waves line up, they add together, creating a bigger wave and brighter light. When peaks meet up with troughs, the peaks and troughs cancel out, creating a smaller wave and dimmer light. Interference is what makes soap bubbles and peacock feathers look so colorful. In bubbles, constructive interference happens between the waves reflected from the outside surface and those reflected from the inner surface, so that each color (i.e., each wavelength) appears very strong in some places and very dim close by (Figure 1A)."

"That is so interesting!" says the referee. "Can you tell us more about diffraction?"

Team Light's second member sits up proudly. "**Diffraction** is observed when a wave encounters an obstacle and bends around it. Diffraction allows us to see sun rays even when the sun is hidden by a cloud. Diffraction can also be observed if waves are forced to pass through, or bounce against, very small openings. This can happen on the surface of a CD: white light hits the thin lines on the CD's surface and they act like a prism, splitting light in multiple colors as it bounces off" (Figure 1B).

Just then, Team Sound presses their buzzer!

"But sound is a wave, too!" shouts their captain. "When sound waves experience interference, the same thing happens. Interference is what makes noise-canceling headphones work." Team Sound goes on to explain that sound diffraction can enable sounds to travel in unexpected directions. For example, traffic noise can reach houses even if they are behind a barrier (Figure 1C). The famous "whispering galleries" in St. Paul's Cathedral, London, and New York

WAVELENGTH

This is the distance between two following peaks (or troughs) in a wave. It is typically used as unit of scale to decide how big are the objects compared to the wave. While for visible light the wavelength is very small, smaller than the smallest hair, the wavelength of the sounds we can hear varies between about 1.7 cm and 1.7 meters. It is worth noting that each primary color has its own wavelength. More on this on the article "A Science Busker Guide to sound".

INTERFERENCE

This is a phenomenon that happens when two waves of the same frequency overlap in the same location. In a nutshell, if their peaks and troughs are in the same location at the same time, they add up...and a louder sound is obtained. Otherwise, they cancel out. More on interference in the article "A Science Busker Guide to sound" and on BBC Bitesize.

TWO-SLIT EXPERIMENT

Imagine a source of red light (on the left) in front of a screen with two vertical slits (in the middle). Light passes through the slits and we observe it on a screen on the right. When a single slit is open, on the screen appears a spot of light. When the two slits are both open, on the screen appears a pattern of lines, alternating dark and light. More can be found on Britannica Kids.

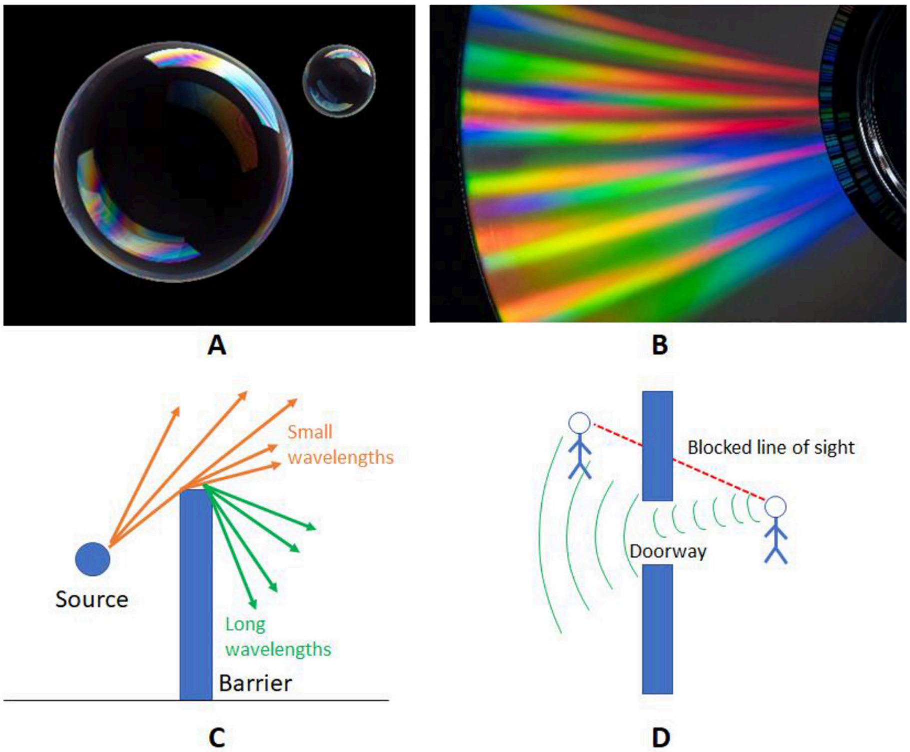

Figure 1

(A) Interference pattern over the thin film of a soap bubble. **(B)** Diffraction on the surface of a CD. **(C)** Sound diffraction can cause traffic noise to make it past a barrier, because the wavelength of the low-frequency noise is bigger than the barrier. This "leakage" of sound is a common problem when designing barriers for motorways, which is solved by adding hat-shaped elements on top of the barrier: these trap the long wavelengths and therefore make the barrier more effective. **(D)** Sound can also "go around a corner," even when line of sight is blocked. This happens because diffraction transforms the doorway into a source of sound itself (photograph credits: A, B iStockphoto.com).

DIFFRACTION

This is a phenomenon that occurs when a wave hits something of a similar dimension as their wavelength: many smaller waves come out from the corners. Imagine a sea wave hitting a rock. More can be found on BBC Bitesize.

City's Grand Central Station work the same way. A person speaking really quietly at one spot under the huge domed roof can be heard on the other side of the dome because sounds of higher frequency (like the ones produced while whispering) cling to the surface of the dome and travel longer distances than those produced while talking normally. Diffraction also makes sure that you hear your parent's voice calling you for dinner even when playing behind a corner (Figure 1D) and that ticket holders at a concert can hear the music quite well, even if they are sitting behind a pillar.

"Fantastic!" cries the referee. "That is one point each!"

ROUND 2: WAVE OR PARTICLE?

The second member of Team Light is next to press the buzzer. After a pause for effect, she proclaims: "Light is a wave and a particle, too!", which receives a round of applause from Team Light's supporters.

PHOTON

This is the particle of light. The name comes from the Greek word "photos," which means light.

The referee looks puzzled. "Really?" she asks. "Tell us how!"

"It is extraordinary to imagine how something can be both a wave and a particle at the same time," says the Team Light member. "But it is true! We call a particle of light a **photon**."

"Interesting," says the referee. "Would anyone from Team Sound like to respond?"

"Actually," says the third Team Sound member, touching the brim of her spectacles, "In 2019, a team of scientists proved that sound waves also involve particles. They even trapped a single sound particle, called a **phonon**. We think that this discovery may be used in quantum computing in the future."

PHONON

This is the particle of sound. The name comes from the Greek word "phonos," which means sound.

"That is 2-all then!" the referee announces.

ROUND 3: THE ROLE OF DEVICES

Team Light presses the buzzer again. "Light can be delivered and controlled with high precision!" says the third member. He describes that, as far back as 800 years ago, monks used magnifying glasses (which bend light) to help them copy ancient books. They describe laser pointers, used to create special effects in movies and entertainment parks (Figure 2A). Then, Team Light's captain asks the audience, "Does anyone have a £5 note I could borrow?" An audience member hands one over, and the team captain points out the note's hologram of Big Ben, London's famous clock tower. "We are so good at controlling light that we can make images seem three dimensional, even though they are flat! We call these images "holograms"" he says.

"After centuries of using lenses, mirrors, and filters, we have achieved such great control of light that most of us now carry a light-controlling device in our pockets, every day!"

"And what might that be?" asks the referee.

The captain pulls out a mobile phone. "This incredible device" he says smugly, pointing to the display "controls light very precisely to make images!"

Supporters of Team Light cheer enthusiastically. Surely, this is the end for Team Sound!

But Team Sound has more to say. "Until 10 years ago," one of them says, "sound technology was very far from having such a level of control. We simply did not have the right tools. Scientists and engineers could only make sure that everyone could get the same sound—or the same silence, in the case of unwanted noise. At concerts or in auditoriums, speakers are assembled in special configurations, to make sure everyone in the audience experiences the same sound quality (Figure 2B). In cinemas, the feeling of being surrounded by sound is achieved by hiding speakers everywhere, including behind

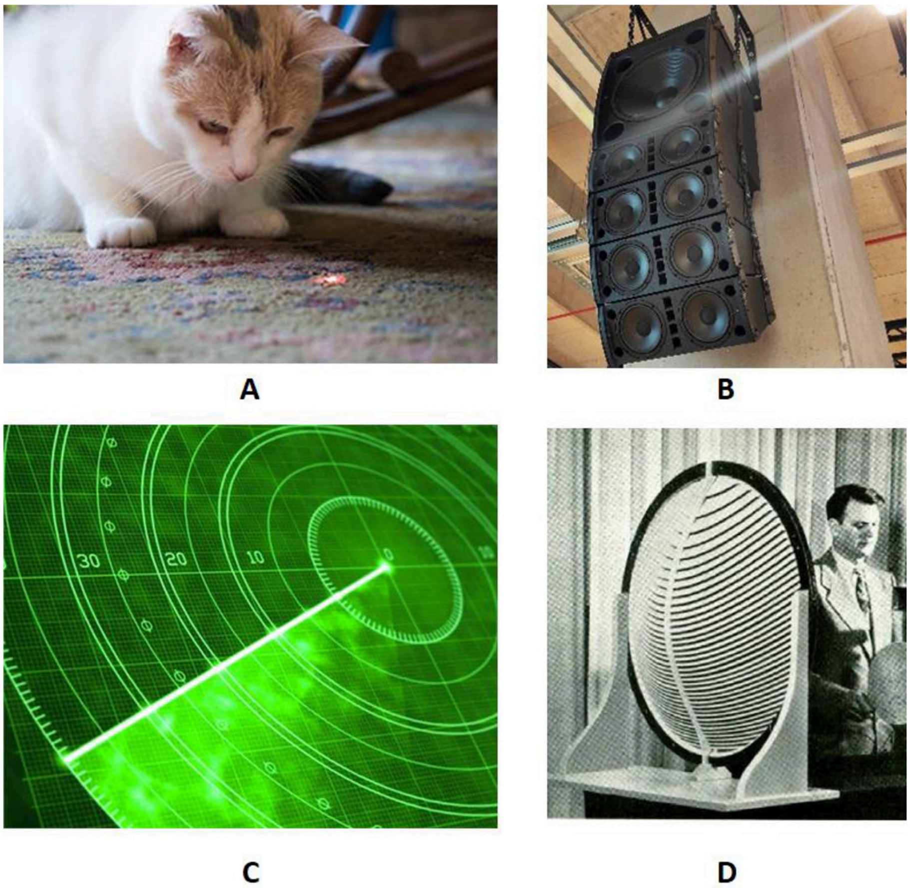

Figure 2

Figure 2

We use devices based on precise light or sound delivery in our everyday lives. **(A)** A cat playing with the spot of light coming from a laser pointer. **(B)** Speakers can be arranged, typically along the shape of the letter "J" or of a banana, to maximize sound delivered in a certain direction, as you might have experienced at concerts or simply in the assembly room of your school. **(C)** Sonar uses a beam of sound to detect objects underwater, for instance obstacles in a submarine. The shape is created by interference, caused by controlling electronically the timing of different ultrasound speakers. **(D)** An early acoustic lens built at Bell labs in 1950s. In the picture, that can be found here, the lens (center) is as big as the engineer on the right (photograph credits: iStockphoto.com).

the screen. Until very recently, personalized sound delivery was only available using headphones."

"Tell us more, Team Sound," says the referee.

"Well," continues the Team Sound member, "in more advanced speaker arrangements, a computer acts like the conductor of an orchestra, telling each speaker when to "sing," and using interference to deliver sound in some places but not others. Speaker configurations like these are what make **sonar** work. Sonar has been used since 1930s to "see" underwater (Figure 2C). The same technology is used in hospital probes that can "see" inside the body using sound. Speakers can be used to deliver a scanning beam of sound to see where there is no light, or even a beam that follows a moving target. But this technology needs many speakers to work properly. **Acoustic lenses**, which would not require electronics, were explored in the 1950s, but until a few years ago they remained bulky and were only practical for high-pitched sounds, which have small wavelengths (Figure 2D). The way we worked with sound was centuries behind the way we could work with light."

SONAR

SONAR: a sound-based device that is used to determine the size and the distance of objects underwater. Originally invented for detecting submarines, it is now used to detect fishes during fishing trips, obstacles during navigation and sunken ships. It works using different acoustic sources that interfere with each other to create a scanning beam. The acronym "sonar" stands for "SOund, NAvigation and Ranging". More on Britannica Kids.

A second team member interrupts, "But then, in 2011, scientists developed **acoustic metamaterials**. These are common materials, like wood, plastic, or metal, engineered so that they can shape the sound that hits or passes through them. Metamaterials were first used to manipulate light in extraordinary ways—they can even make an object invisible! But use of metamaterials to manipulate sound will make a huge difference to our lives. Metamaterials now allow us to make acoustic lenses that can focus sound in a small spot, like the sun through a magnifying glass, and even acoustic holograms, which can bend sound waves into 3D complex shapes!"

The referee is impressed. "That is amazing," she says. "But what are acoustic metamaterials?"

WELCOME METAMATERIALS!

Here is what Team Sound has to say:

"Earlier, we talked about wavelength and how sound and light can be changed by interference and diffraction—by making light or sound waves bump into each other.

Visible light has a wavelength between 400 and 800 billionths of a meter. That is pretty small! But sound waves have much bigger wavelengths. A typical child can hear sound with a wavelength between 17 millimeters and 17 meters. Because metamaterials are engineered at a scale much smaller than the length of sound or light waves, they are tricky to make for light. But for sound, with its larger wavelengths, creating metamaterials is a lot easier. Objects that are smaller than the wavelength of sound can actually be made with a standard 3D printer!"

Another member of Team Sound adds, "Acoustic metamaterials are made of small parts, called unit cells or bricks (Figure 3A). The shapes of these unit cells is what does the trick: they are precisely designed so that each cell uses diffraction and interference to modify the sound going through it. We can use them to change the intensity of sound or to delay—or even trap—sound (for more information on basic metamaterials, please see this Frontiers for Young Minds article). We can now apply the knowledge gained from studying light to solving problems in acoustics."

"And," adds the team captain, "only a limited number of unit cells is needed [1]. Just like any word can be made from various combinations of just 26 letters in the Latin alphabet, we can make acoustic metamaterials from a collection of just 16 different bricks. Bricks can be used like building with LEGO®—we can assemble them into useful structures such as lenses, that can fit into the palm of the hand (Figure 3B). When unit cells work together, they can achieve incredible feats"

ACOUSTIC LENS

Acoustic lens: a "lens" is a common device when we are talking about light. For example, a magnifying glass or the lenses used in spectacles to correct shortsightedness or in telescope objectives. An acoustic lens is a device that has the same effects, but for sound. A converging lens (for sound) would focus the emission of a loudspeaker in a spot. A diverging lens (for sound) might be used to send the high-frequency of a loudspeaker over large angles. More on lenses for light on Britannica Kids.

ACOUSTIC METAMATERIALS

It is a new type of materials, where the properties do not come from the chemistry of the base material, but from how it is engineered. The key point is that the engineering needs to be precise enough to work at a scale smaller than the wavelength. More on the definition of what is a metamaterial can be found here.

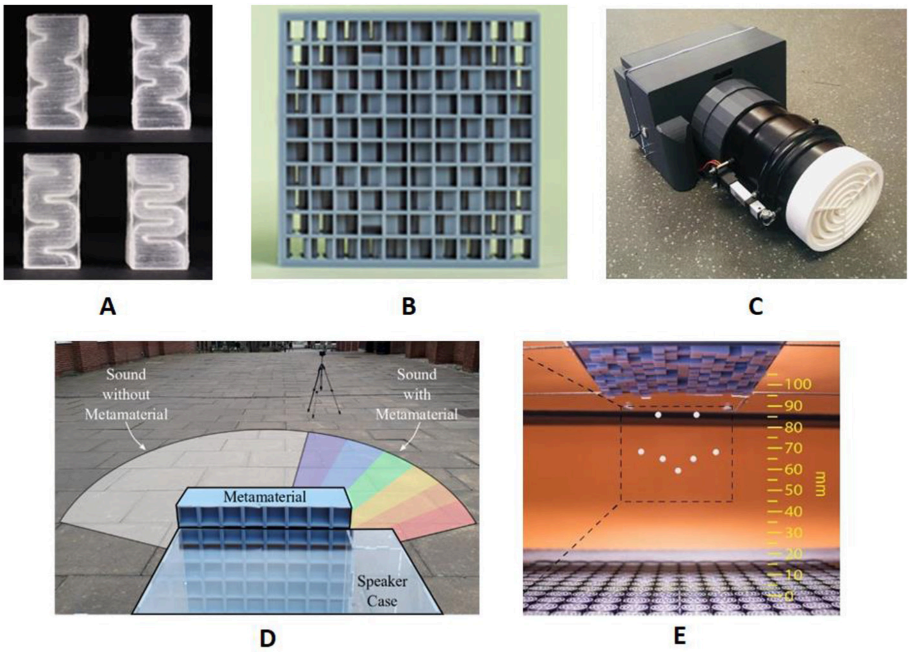

Figure 3

Figure 3

(A) Metamaterials bricks (2 cm × 1 cm in the picture) are designed with winding paths inside, which the sound must travel through. The longer the path, the longer the sound is delayed inside the brick. **(B)** Lenses are one possible way to assemble metamaterial bricks. Acoustic lenses could be used to send messages to single person in a crowd or to create the acoustic equivalent of a lighthouse, with a beam of sound delivering messages along a line of chairs in a theater. Each square brick in this lens is 1 cm in size, so the whole lens is as big as the hand of a human adult. **(C)** In this levitation experiment with multiple objects, the speakers are at the bottom and the metamaterial is on the top. The polystyrene balls are held in traps made of sound, whose shape is encoded in the metamaterial. **(D)** A sound projector. Two metamaterial lenses (white), like the one in **(B)**, are attached to motors that change their mutual distance. Using a movement sensor, like the one used by the XBOX console, allows acoustic signals to be delivered to a moving person. **(E)** In this experiment, the metamaterial placed in front of the speaker acts like a prism, splitting melodies (that contain multiple notes) into an "acoustic rainbow," where each note goes in a different direction, like the colors in a rainbow (photograph credits: Sussex University).

(to read more about the acoustic superpowers of moths, see this Frontiers for Young Minds article).

He continues, "Acoustic lenses are based on diffraction but can be used to magnify and direct sound, just like lenses for light. We can use these lenses to set the direction of sound from loudspeakers and, like a lens for light creates the beam of a lighthouse, we can shape a beam of sound that travels great distances. Imagine how this might help us deliver sound effects in a cinema or theater [2]!"

The second member of Team Sound adds, "We can also combine two acoustic lenses, similar to the way optical lenses are used in cameras and telescopes. By adjusting the distance between the lenses, we can deliver sound to a specific location. We can use a programmable circuit board and a motor, in a set-up that looks like a camera, to create the acoustic equivalent of "autofocus" (Figure 3C), which we can deliver sound to a moving person, tracked by an Xbox Kinect [3] . With further development, sound delivery in a crowded school cafeteria will be possible. Line cues could be sent to actors on stage without using headphones. Acoustic metamaterials could allow customers more privacy when talking to bank staff, doctors, receptionists, or inside a booth in a cafe."

There is no stopping Team Sound now! The third team-mate takes over:

"We have also explored acoustic diffraction. Inspired by the rainbows on CDs, we created an experience called "acoustic rainbows" [4].

The experience is simple: a metamaterial is placed in front of a speaker, so that it splits the music going through, sending the notes in different directions (Figure 3D). We played pieces of music, made by different local composers, and asked people to describe what they felt while exploring the space in front of our metasurface. They used the language of light and vision, talking about colors rather than sounds. They told us that, while they had learnt about colors in primary school and could recognize the changes in sound during the experience, they did not have the right words to describe what they called "an acoustic rainbow." Perhaps acoustic rainbows could be used by musicians to interact playfully with their audiences, by sending different notes to different places! This could transform our experience of music! Just imagine how our projectors could transform virtual reality experiences!"

"And finally," concludes the captain, "3D-printed surfaces made of bricks, thinner than one wavelength, have been used to create acoustic holograms, and the precision of these sculptures made of sound has been used to levitate small objects in mid-air using sound and even multiple objects in the shape of smiling faces [5] (Figure 3E)" (to read more about levitating objects using sound, see this Frontiers for Young Minds article).

AND THE WINNER IS...

"There is so much incredibly exciting work going on in acoustics!" says the referee. "The acoustic metamaterials you describe sound amazing and I am really looking forward to finding out more about them!" Then, Team Sound plays their trump card: "We believe that acoustic metamaterials will even give us silent hospitals and offices!" Everyone starts clapping.

With the scores standing at three-all, the referee concludes, "We will definitely need a re-match in a few years' time. Congratulations to both teams for all your fantastic work!"

Which team do you think might come up with the next great invention? Perhaps *you* will decide the winner one day!

ACKNOWLEDGMENTS

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YOUNG REVIEWERS

GINNY, AGE: 13
Ever since I was a little girl, I grew up in the world of science and I found my love for math and computers. I decided to work as a Young Reviewer as it would give me the opportunity to learn how scientific papers are published. I love to read and be with my friends. I am so excited to see what adventures are in store for me in the future.

JIARUI, AGE: 13

My name is Jiarui, and I am a 8th grader at a middle school in China. I won national prizes in English speech contests and state awards for coding. I like piano, and have gotten the Grade 8 Certificate of ABRSM with a distinction score. I am very excited about physics. I like baking and cooking. I love dogs and have two poodles.

AUTHOR

GIANLUCA MEMOLI

Gianluca has been working with sound since 2004, both in industry and in academia. A physicist, an engineer and—according to his two children—an inventor, Gianluca is passionate about amateur dramatics. He received the UK prize for Communicating Acoustics to the Public in 2013, after talking about his research to more than 66,000 people. *g.memoli@sussex.ac.uk

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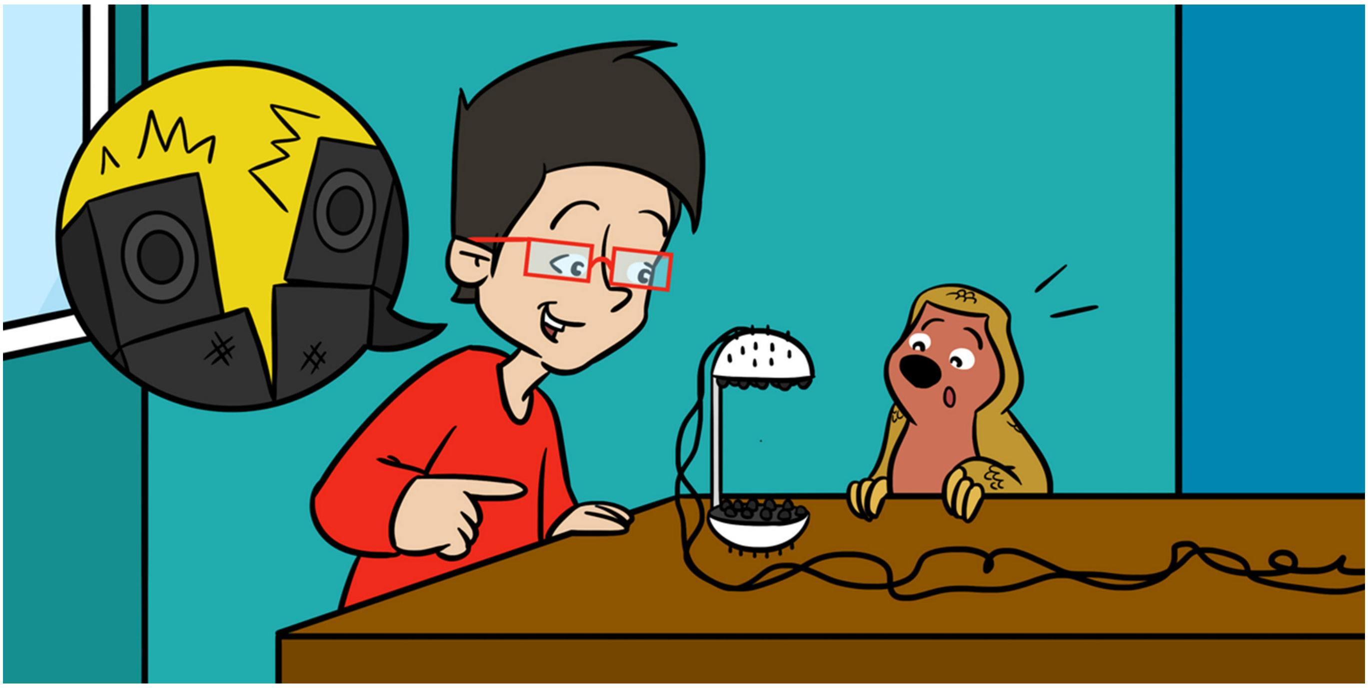

LEVITATING OBJECTS USING SOUND

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YOUNG REVIEWER:

YARDEN

AGE: 13

Acoustic levitation uses sound waves to hold objects in mid-air. We are all familiar with the power of sound to make us dance and change our moods, but sound can also exert a physical force that is strong enough to levitate objects. To harness this force, we use loudspeakers to form a sound pattern so that the object is surrounded by very loud sound. Scientists have used these ideas to levitate small objects such as insects, as well as extremely small objects like individual cells. They can then manipulate these objects, much like a robot would, but without any moving parts. So far, only relatively small levitating forces have been generated but, in theory, much higher forces could be produced and levitation of objects even the size of humans might be possible. Despite this exciting possibility, you might not want to be acoustically levitated yourself, for good reason!

WHAT IS ACOUSTIC LEVITATION?

The idea of hovering gently in mid-air is an exciting one. You could travel large distances with little or no effort, visit inaccessible places, or just sit back and relax! People have been thinking about levitating themselves or objects for a very long time, but these ideas still seem a long way from being possible. Levitation is also popular in films, usually with no explanation of how it works. Some people have claimed to have this seemingly magical power, but these claims have not stood up to scientific investigation. However, **acoustic levitation**, which means using sound waves to hold objects in the air, is a scientific fact. This article describes how acoustic levitation works and what might be possible now and in the future.

ACOUSTIC LEVITATION

The use of high amplitude sound waves to overcome gravity and hold objects in mid-air.

Sound is created when something vibrates and creates waves of energy. The vibrations travel through the air to our ears. The stronger the vibrations of the air molecules, the louder the sound. Sound waves carry forces, although these are usually too small to feel. An extreme version of this effect is an explosion. The explosive force is carried by a shock wave, which is a very high amplitude sound wave. This tells us that sound waves can carry forces through the air and that these forces can be quite large. As you can imagine, these forces will act on any material, including living things. But how can we harness this force in a safe and controllable way?

Loudspeakers are sources of sound that we are all familiar with. If we could find a powerful enough loudspeaker, could it help us achieve levitation? The answer is part yes and part no! Yes, in that a powerful loudspeaker could apply a force to an object placed in front of it. No, in that a single loudspeaker would provide a pushing force only, and the object would be uncontrollably blasted forwards. To stabilize the levitation, the trick is to use lots of loudspeakers and combine the sounds from all of them.

ARRAY

Many sources used together to create a combined effect. The term applies to any energy source, but here we use it to mean a collection of loudspeakers, each contributing to create a loud sound at a point.

A group of loudspeakers arranged to combine the effects of their sounds is called an **array** (Figure 1). We must carefully control the timing of the sound coming from each loudspeaker. If we get this timing right, the sound waves will come together to form the pattern of loud and quiet regions needed for acoustic levitation. The key ingredients of this sound pattern are a quiet region where the object will sit and loud regions that will surround the object, like a cage of loud sound. If the object tries to move, it is pushed back by the sound to the quiet region.

DECIBEL (dB)

The international unit of measurement for sound loudness. For example, normal conversation is 60 dB, a police siren is 120 dB and fireworks or very loud music is 140 dB.

To levitate even light objects, we need very loud sounds. Sound loudness is measured in **decibels**. Normal speech is around 60 decibels, loud rock music 140 decibels, and a rocket during launch 180 decibels. Levitation of extremely light things starts when the sound is around 145 decibels, which is just above a loudness level called the threshold of pain. At this loudness, the sound will be not just loud, but painful and potentially damaging to our ears! The solution is to use **ultrasound**, which is sound with a pitch too high for humans to hear; although animals such as cats and dogs can hear it. Even though we cannot hear it, ultrasound still contains energy in the form of vibrating air molecules, which can be used for levitation (Figure 2).

ULTRASOUND

Sound at pitches above 20 kHz. This is the typical upper limit of hearing for healthy adults. Many animals such as cats, bats, insects, and dolphins can hear these sounds.

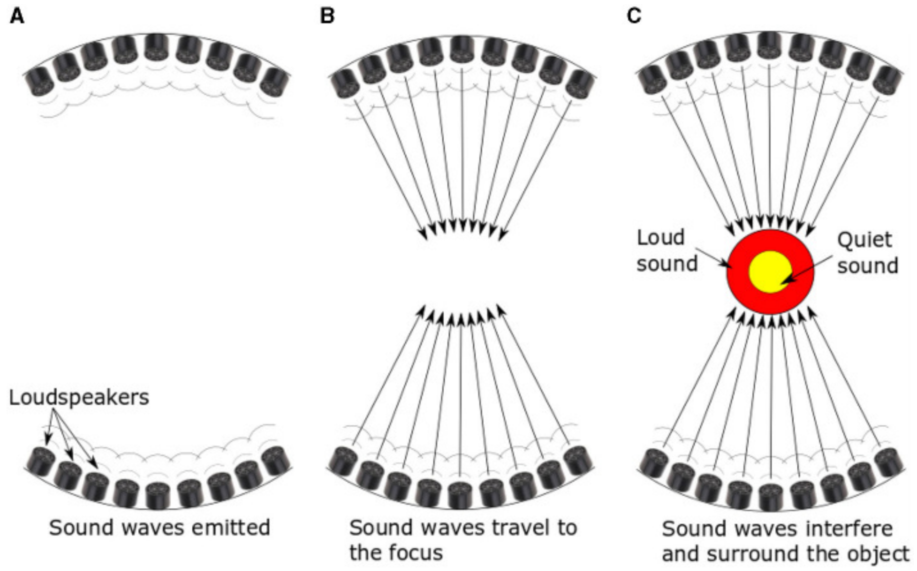

Figure 1

Figure 1

How acoustic levitation works. **(A)** Two arrays of loudspeakers, each shaped like a bowl, are activated to emit a loud sound. **(B)** The bowl shape causes the waves travel to travel to a center point, where the loudness is even greater. **(C)** The waves mix together in a process called interference. If the timing of the waves is just right, this interference creates a quiet zone surrounded by very high loudness. Objects sitting in the quiet zone can be levitated, if the sound is loud enough, because the force of the loud sound will keep them in the quiet zone.

CAN MAGNETS BE USED FOR LEVITATION?

When you use a magnet, you quickly find that forces can be applied to certain metal objects at a distance. The magnet will attract certain metals with a force that is hard to resist. Hold a magnet in each hand, then bring them together and you really get a sense of this force. Scientists found that these magnetic forces can be used to levitate objects, but that it only works on objects made from magnetic materials, such as iron. Normal magnets cannot apply forces to living things. However, if the strength of the magnet is extremely high, an effect called **diamagnetic levitation** can occur and act on living things. In diamagnetic levitation, the strength of the magnet is so high that it causes the water molecules in the living thing to stretch out and become tiny magnets. The tiny magnetized water molecules can then be pushed by the original magnet. Figure 2 shows a famous experiment in which a 20-millimeter-long frog was held in mid-air using diamagnetic levitation [1]. But a huge amount of power (enough for around 500 homes!) was needed to power the magnet.

DIAMAGNETIC LEVITATION

The use of very strong magnetic fields to magnetize materials and then hold them in mid-air. This effect has been used to levitate living things such as a small frog.

IS IT DIFFICULT TO MAKE AN ACOUSTIC LEVITATOR?

It may surprise you to learn that you can build your own acoustic levitator at home. A group of researchers have written instructions and made a video explaining the steps involved [2–4]. The main parts needed are loudspeakers, an amplifier, and a signal generator (Figure 3). These are the same parts that make up a radio or any sound system. First, the signal generator makes the wave as an electrical signal. The signal is boosted by the amplifier and fed to the loudspeakers. If the electrical signal is increased, the loudness coming from the

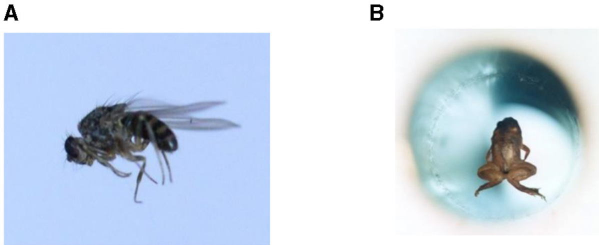

Figure 2

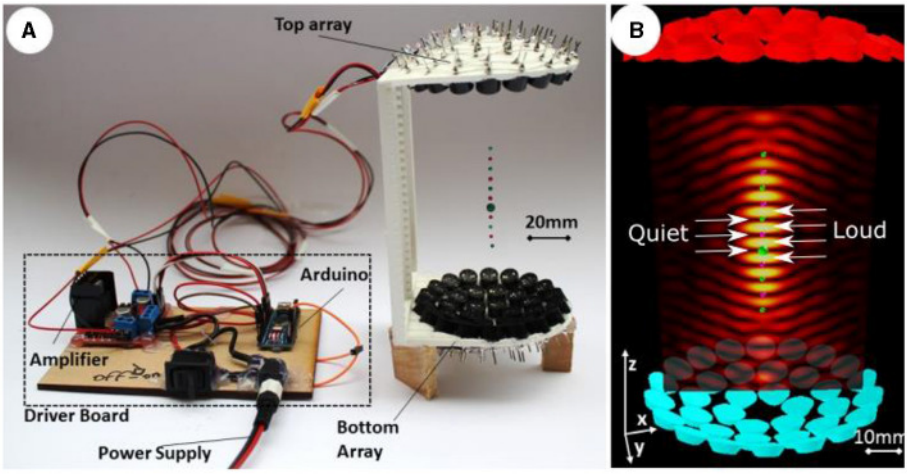

Figure 3

Figure 2

(A) Acoustic levitation of a 5-mm-long fruit fly. **(B)** Levitation of a 20-mm-long frog, with another type of levitation called diamagnetic levitation. The fly and frog were not harmed (Image credit: [1]).

Figure 3

An acoustic levitator that can be built at home. **(A)** The parts on the driver board include an Arduino computer that generates the electrical wave and an amplifier to boost the wave. This electrical signal is sent to an array of ultrasound loudspeakers assembled into bowl shapes. The levitator can be powered by a battery or a household electrical socket. **(B)** Map of the loudness pattern. Yellow is loud, black quiet, and red in-between. The levitated objects sit in the quiet regions, held in position by the loud regions above and below (Image credit: [3], CC BY).

STANDING WAVE

A wave that has a fixed pattern of high and low amplitudes. This can be seen by shaking a slinky up and down at the right speed. You will see a series of points where the slinky is stationary and between them other points where the slinky is moving wildly.

INTERFERENCE

The result of two or more waves of any type mixing. Drop two stones in a pond. The circular waver waves will spread out. When they mix it is called interference.

loudspeakers increases. This is just what happens when you turn up the volume on your car radio.

The loudspeakers used in a levitator are a bit special because they emit ultrasound. They are originally made as parking sensors for cars, but we repurpose them as ultrasound loudspeakers. If we connect enough of them together and feed them with strong enough electrical signals, we can create sound loud enough for levitation. This experiment uses ultrasound, so it is beyond anything humans can hear. This makes the experiment seem quiet to humans. But, in the area where the levitation happens, the air molecules are shaking violently.

When building a levitator, it is important to get the right pattern of quiet and loud regions. In the home-built levitator, this is done by arranging the loudspeakers in two focusing bowls, which concentrate the energy into a point. When the two bowls are facing each other, a repeating pattern of quiet and loud sound is formed. This is known as a **standing wave**, and it forms when waves meet and mix together in a process called **interference**. You can create a standing wave yourself by shaking a skipping rope or a slinky spring. At certain shaking speeds, you see a fixed pattern of highly vibrating parts and stationary parts. This pattern is exactly what is needed for levitation, with the objects being levitated in any of the quiet regions.

WHAT ARE THE APPLICATIONS OF ACOUSTIC LEVITATION?

So far, scientists and engineers interested in acoustic levitation have put most of their efforts into levitating objects only a few millimeters in size, such as insects or electronic parts. Holding insects and other living things in place allows us to carefully study them under a microscope without touching them, which is important if they are extremely delicate. We can also levitate the small parts used to build a mobile phone, using the levitation device to pick them up and move them from one place to another, just like a robot arm.

Acoustic levitation can also be used to manipulate even smaller things, such as living cells. These devices are being used like microscopic grippers. One particularly exciting application is in tissue engineering, in which scientists are trying to find ways of recreating skin or muscle. In this case, the acoustic levitation device is used to arrange the cells into specific patterns. Cells have recently been assembled into lines, to form a new piece of muscle [5]. Muscle grown in this new way was shown to be better than muscle grown with any other known laboratory method.

THE FUTURE OF ACOUSTIC LEVITATION

Exciting discoveries can be expected in the next few years in the field of acoustic levitation. Now that acoustic levitation has been used to make simple tissues like muscle, the next step is to use it to assemble more complex structures, such as artificial hearts. Ideas like this will require engineers to collaborate closely with medical researchers.

What might be possible in terms levitating larger objects? Might it ever be possible to levitate humans? Although hard to believe, levitation of humans is possible in theory—we just need to produce loud enough sound over a human-sized area. Calculations suggest that the loudest loudspeakers ever made would allow us to levitate frogs. There is no reason that even louder loudspeakers could not be made, given the will and the money! If possible, would *you* like to be levitated?

A wide variety of small insects and even fish have been acoustically levitated. They have also been carefully observed under a microscope and found to be unharmed. To levitate larger objects, louder sound is needed, which means more energy. The danger is that the energy must go somewhere, and it could be absorbed by the objects or the air around the objects. All this energy could result in dramatic and rapid heating, which might be harmful. In addition to this heating danger, the effect of such loud sounds on living things is just not known. So, while acoustic levitation of humans is possible *in theory*, there is still work to be done before we can do it safely.

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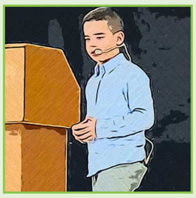
YOUNG REVIEWER



YARDEN, AGE: 13
I was born and raised in Israel. My main hobbis are KAMI (israely martial art) and rhetoric. I have a brown belt in KAMI and I won second place in the Israeli "young speaker" competition. I am also in the scouts and I like to sing.

AUTHOR

BRUCE W. DRINKWATER
Bruce Drinkwater is Professor of Ultrasonics at the University of Bristol. He has a passion for all things ultrasonic and acoustic. As an engineer, he is particularly interested new ultrasonic technology and new applications. He has used ultrasonics

to monitor the safety of engineering structures, detect if bearings are about to seize and levitate many different objects. One of his career highlights is being quoted as the inventor of a fictional sonic vortex weapon in an episode of Marvel Comics'. The Indestructible Hulk. *B.drinkwater@bristol.ac.uk

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BIODIVERSITY
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THE SECRET SUPERPOWER OF MOTHS: SOUND-ABSORBING STEALTH CAMOUFLAGE

Marc W. Holderied *

School of Biological Sciences, University of Bristol, Bristol, United Kingdom

YOUNG REVIEWER:

BRYSON
AGE: 8

Today's military aircraft typically use highly engineered "stealth" coatings that make them almost invisible to radar. Nature might seem an unlikely place to find such advanced technology, but one should never underestimate the ingenuity of evolution—moths developed their own form of stealth cloaking over 60 million years ago! That is before humans even walked the Earth! We discovered that the tiny scales on moth wings, which form fine dust when touched, provide stealth camouflage against the sonar used by their most dangerous foes—bats. By absorbing bats' high-pitched calls, moths become nearly invisible to bats. Such stealth camouflage is a true superpower, as the coating on moth wings is light enough to allow flight, while still absorbing all the sounds bats make. The moths' trick is that scales of various shapes work together to create a powerful super-absorber that is now inspiring humans to develop new sound-absorbing materials of our own.

EVERYBODY WANTS TO CATCH A MOTH

The life of a moth is full of dangers. Whether a moth is hiding during the day or flying at dusk, predators will be on the prowl, trying to catch a tasty snack. Spiders, birds, monkeys, bats, and even the grizzly bears of the Rocky Mountains love to feast on juicy moths[1]. To make things worse, moths do not have hard armor or stinging tails to protect themselves. Instead, evolution has equipped moths with a remarkable defense that no other insect has: a dense coat of hairs and scales made from a substance called chitin, which helps moths to evade and escape many kinds of predators (Figure 1)!

[1] Main, D. 2015. *Grizzly Bears Can Eat 40,000 Moths in a Day*. Newsweek. Available online at: `https://www.newsweek.com/grizzly-bears-can-eat-40000-moths-day-400281`.

A moth's entire body, except its eyes and wing joints, is densely covered in these hairs. They form a sort of dense fur on the main parts of a moth's body and they are flattened into overlapping spade-shaped scales on the wings. But how can fur and scales protect a small moth from being eaten by a spider, a monkey, or a bat? Amazingly, a moth caught in a spider's web can escape because the scales that are stuck to the web simply break off at their bases. Parallel ridges on the scales make them slippery, helping moths to slide out of a monkey's grasp or a bird's beak. Also, birds and other predators looking for prey are fooled because the scales create camouflaging or confusing color patterns [1]. But the most amazing thing of all is that the scales actually help moths hide from their most fearsome predator—bats.

HUNTING WITH SOUND

Most bats hunt at night. While other night-time predators, like owls, have incredible eyesight to help them spot their prey in the dark, bats find their way around using sound. We call this **echolocation**. Bats make tiny squeaking sounds that bounce off nearby surfaces, creating echoes that the bats then pick up with their sometimes-enormous ears. Bats have extremely sensitive hearing—they can move around in complete darkness and can tell whether their squeaks have echoed

ECHOLOCATION

Some animals emit sounds and then listen for the returning echoes which help them paint an acoustic image of the world even in complete darkness. A bat's super-power.

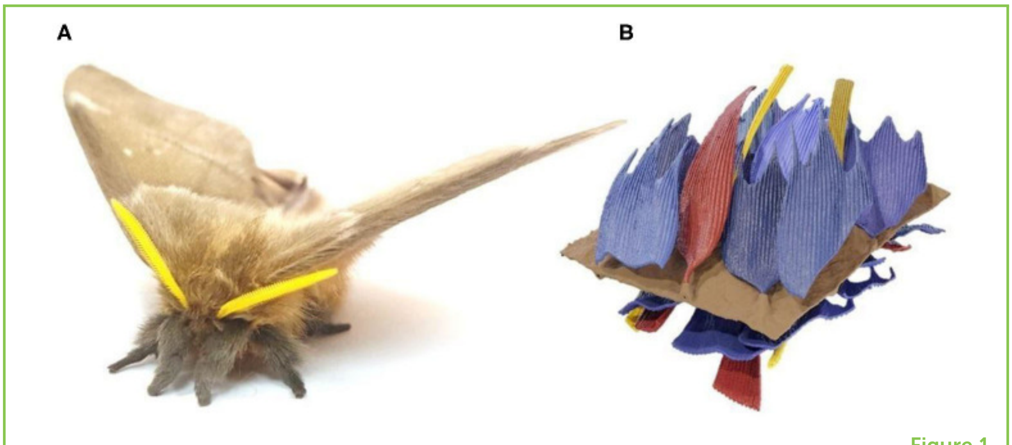

Figure 1

Figure 1

(A) A very furry silk moth (Photograph credit: T. Neil). **(B)** A microscopic false-color image of a small section of a moth wing, showing spade-shaped (blue), lanceolate (red), and hair-like (yellow) scales on both sides of the brown wing membrane (3D model: S. Reichel).

off a tree, a building, or a flapping insect such as a tasty moth. We call this bio-sonar and it is a bat's superpower!

How, then, can a moth defend itself against such an ingenious biosonar? Some moths have ears and can hear the calls of an approaching bat and fly away. But most moths are deaf and do not even notice when they are under attack by a bat. Instead, they rely on the amazing ability of their hairs and scales to absorb, or soak up, the bats' squeaks rather than reflecting them back to the bats' ears. We might say they have an **acoustic** "stealth cloak" that helps them disappear from a bat's biosonar. Keep reading to discover the surprising secret behind a moth's stealth cloak!

ACOUSTIC

Anything to do with sound.

THE STEALTHY MOTH IS FURRY

Have you ever been inside a large, echoey building such as a church or large hall? You might have noticed that these spaces do not have many carpets, curtains, or other soft furniture. In our homes, schools, and offices, these soft materials absorb sounds, which helps make these spaces quieter places to live and learn. When sounds hit a hard surface, they bounce off, creating an echo. But when sounds hit softer materials, such as carpets or cushions, they bounce around in the tiny spaces *inside* the material and are trapped and absorbed. We call these tiny spaces pores, so these soft materials are called **porous absorbers**.

POROUS ABSORBER

A material that has many interconnected holes and cavities (like a sponge) in which sound enters and then is absorbed.

In a similar way, the hairs and scales on a moth's body also absorb sounds, including the squeaks made by bats. Sound is created by vibrations moving through the air. The faster the vibrations, the higher the **frequency** of the sound. So, a high-pitched bat squeak will have a high frequency, whereas a low-pitched cannon boom will have a low frequency. Porous absorbers are much better at trapping high-frequency sounds. Even a thin layer can trap the highest-frequency sounds. But to absorb lower-frequency sounds, the porous absorbers must be much thicker. The fur on a moth's body is around 2 mm thick, which is exactly the right thickness to absorb the lowest sounds used by bats for echolocation. In fact, we have discovered that moths with fur are *half as likely* to be caught by bats than moths with no fur [2]!

FREQUENCY

Describes how fast a sound wave oscillates. Fast-oscillating, high frequency sounds have a high pitch and slowly oscillating low-frequency sounds have a low pitch.

SCALY WINGS ARE POWERFUL SOUND ABSORBERS

So, the fluff on the moths' bodies is great at helping them hide from bats. But a moth's wings aren't hairy, so why can't a bat just detect echoes bouncing off the smooth wings? Obviously, a moth's wings would not work very well if they were covered in long hairs, so moths have evolved an even more fascinating way to make sure their wings are hidden too. Moth wings use what is called **resonant sound absorption**.

To understand resonance, imagine you are pushing your friend on a swing in the playground. You must push the swing at exactly the right time to make it go higher and higher. If you push at the wrong time, you can even completely stop it from swinging. We call the timing of this ideal push the **resonance frequency** of the swing. In the same way, objects can have different resonant frequencies for sound.

Sounds travel through the air as waves, rather like the waves on the ocean. The distance between the top of one wave and the top of the next is called the **wavelength**. Porous absorbers, such as the hairs on a moth's body, need to be 1/10 as long or thick as the sound's wavelength to absorb the sound. But resonant sound absorbers only need to be 1/100 as thick as the sound's wavelength, which makes them perfect for moth wings. The resonant absorbers on a moth's wings take the form of spade-shaped flattened scales (Figure 1B). When sound of the resonance frequency hits such a scale, the scale will start to vibrate. The **energy** contained in the sound is turned into kinetic energy, or movement of the scale, which results in the sound being absorbed.

Resonant absorbers, such as the vibrating scales on a moth's wings, only absorb sound at a single frequency. Because bats use many sound frequencies during echolocation, a single resonant absorber would only remove one part of the echo, and the bat could still find the moth by its remaining echo [3]. To combat this, each scale on a moth's wing has a slightly different size and shape (Figure 1B) and, as a result, each scale has a slightly different resonance frequency. In fact, when we looked closely at moth wings, we discovered that they have variously shaped scales that cover all the resonance frequencies of bat's squeaks! Each scale absorbs its own frequency and, together, all the scales absorb all the bat's frequencies. We even found that the overlapping scales interact with each other, making them more absorbent as a group than they are by themselves. This super-absorption power makes moths' wings an **acoustic metamaterial**—a structure so good at absorbing sound it has not yet been found anywhere else in nature [3].

RESONANT SOUND ABSORPTION

Can be 10× thinner than a Porous absorber (see above) and works by many small resonators that each absorb one frequency (see Resonant frequency), and together they absorb all frequencies.

RESONANCE FREQUENCY

An organ pipe, a swing in the playground or a moth scale are all resonators. They respond when stimulated with the exact right frequency—their resonance frequency.

WAVELENGTH

In all types of waves—e.g., waves on the ocean or sound wave—the distance between the top of one wave and the top of the next is called its wavelength.

ENERGY

The ability to do work.

ACOUSTIC METAMATERIAL

A material made from many subunits (like moth scales) whose interaction creates effects going beyond the sum of the individual elements.

INSPIRING SUPERMOTHS

In summary, while moths lack the hard shell of a beetle or the sting of a wasp, they have evolved an incredibly clever way to protect themselves from being found and eaten by predators. Not only do their hairs and scales make moths slippery and difficult to keep hold of, these structures also form one of nature's most complex materials, which acts as a sort of stealth cloak, keeping moths hidden from bats—their most dangerous adversaries (Figure 2).

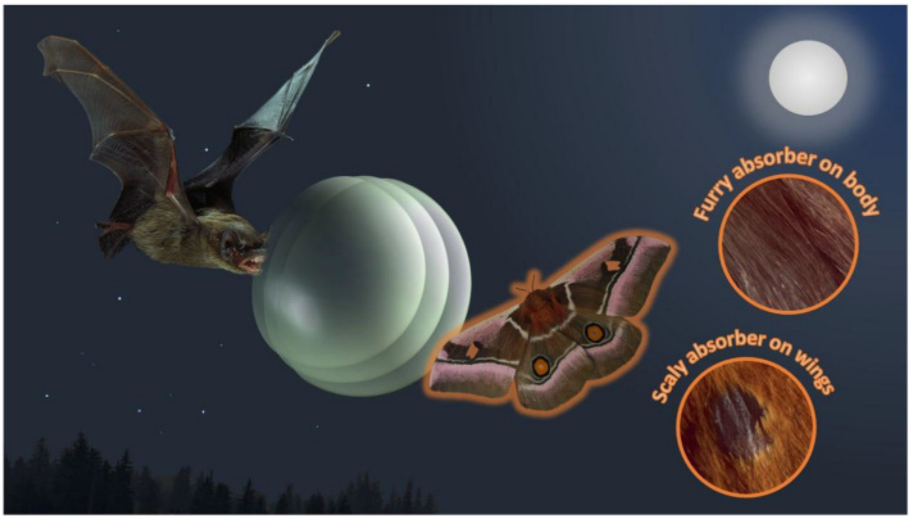

Figure 2

Figure 2

A bat hunting a moth using echolocation. The moth is equipped with a stealth cloak that absorbs the bat's call and protects it against detection by the bat's biosonar. The sound absorber on the body is thick fur and the absorber on the wings is a much thinner layer of flattened scales that form a sound-absorbing metamaterial (Photograph credit: D. Nill and T. Neil).

These tiny superheroes have inspired humans to develop better ways of controlling sound in our own homes, buildings, cars, and airplanes. By understanding exactly how moth wings work, we might be able to build thinner, lighter materials to absorb sound, helping to create quieter, more pleasant environments for us all.

As for staying safe from grizzly bears...unfortunately, no amount of hair or scales can protect moths against these giants. Perhaps one day, a cloud of scales might get up a bear's nose, making him sneeze out his snack and letting our mighty moth live another day. Good luck little moths!

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3. Neil, T. R., Shen, Z., Drinkwater, B. W., Robert, D., and Holderied, M. W. 2020. Moth wings are acoustic metamaterials. *PNAS* 117:31134–41. doi: 10.1073/pnas.2014531117

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YOUNG REVIEWER

BRYSON, AGE: 8
I am Bryson. I am 8 years old and in the third grade. I like to review the papers because I think that they are fascinating.

AUTHOR

MARC W. HOLDERIED
Professor Marc Holderied is a sensory biologist and bioacoustician with strong links to bio-inspired engineering. He researches acoustic camouflage and biosonar navigation, with a continued passion for acoustic arms races and wildlife acoustics. He consults the automotive industry to develop Ultrasonic Vision technology, and he leads the free-for-all Bioacoustics Special Interest Group at UKAN (acoustics.ac.uk).
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AURALDIVERSITY: DO YOU HEAR DIFFERENTLY?

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YOUNG REVIEWERS:


BROOKLYN
AGE: 11


ELISA
AGE: 13


JOAN
AGE: 15


TINA
AGE: 15

This article explores the sense that opens us to the world of sound: hearing. Textbooks often repeat the same numbers and figures on the sensitivity of human hearing, as if we all share the same set of symmetrical mechanical ears. Here, you will discover hearing as we experience it day-to-day: the different kinds and qualities of hearing you, your friends, and your family may have experienced, and how hearing may change as we grow older. We call this real-life approach to understanding hearing auraldiversity. This article will tell you about some important kinds of hearing differences such as hyperacusis, misophonia, and tinnitus, and it will explain the brief changes in hearing sensitivity that sometimes occur, such as after sudden loud sounds. Hearing can open us up to the world in a very powerful way, but we must remember that it is a vulnerable sense that needs protecting from too much loud sound.

NOT EVERYONE HEARS IN THE SAME WAY!

This article explores the sense that opens us to the world of sound: hearing. Textbooks tend to repeat the same numbers and figures on the sensitivity of human hearing as if we all share the same set of symmetrical mechanical ears. As you read this article, you will discover hearing as we experience it day-to-day: the different kinds and qualities of hearing that you, your friends, and your family may have experienced, and how hearing may change as we grow older. We call this real-life approach to hearing, **auraldiversity** [1, 2].

AURALDIVERSITY

Difference in our hearing from each other and how it changes throughout our lives.

THE HEARING SYSTEM IS INTRICATE AND COMPLEX

Hearing means using the ears to receive sounds and to recognize, understand, enjoy, or be annoyed by them. The ears include much more than the visible flaps on the sides of the head. The flaps are part of the outer ear, called the pinna, and they play an important role in how we get information about the space around us from the sounds we hear. The ears are one of the most intricate and compact organs because they have so many parts, including tiny bones, which must all work together. In addition to the outer ear, the hearing system includes the middle ear and the inner ear, as well as the nerves and the brain (Figure 1). When a person's hearing is not working as well as it could be, hearing professionals called audiologists or otolaryngologists can try to find out which part or parts of this complex system are at fault.

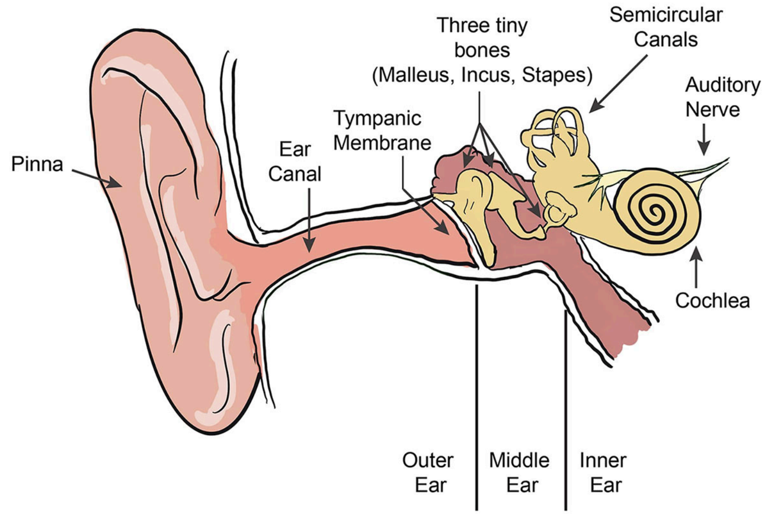


Figure 1

Figure 1

The anatomy of the ear.

Hearing involves more than just the ears! Depending on the situation, the senses work together to help us understand and navigate the world around us. For example, you might not realize it, but you probably watch people's lips, eyes, and eyebrows moving when they speak. When you do so, your vision is helping your hearing to understand what is being said!

SOUND IS VIBRATION

Sound travels through the air, water, and other materials as vibrations. If sounds are low in frequency and full of energy, we can even feel them in our bodies. Think of standing at the roadside when a bus passes by. You may hear a loud, low rumbling in your ears and feel it in your feet and skin. The percussionist Dame Evelyn Glennie, who has been deaf since she was 12, wrote:

> Hearing is basically a specialized form of touch. Sound is simply vibrating air which the ear picks up and converts to electrical signals, which are then interpreted by the brain. The sense of hearing is not the only sense that can do this, touch can do this too... Deafness does not mean that you cannot hear, only that there is something wrong with the ears. Even someone who is totally deaf can still hear/feel sounds [3].

Glennie encourages her audiences to hold balloons in their hands so that they can use their sense of touch to help them enjoy the vibrations set into motion by the music.

MEASURING HEARING

Hearing is measured by comparing the relationship between two qualities of sound: frequency and loudness. Frequency, or how high or low a sound is, is measured in Hertz (Hz). Young adults can normally hear sounds from 20 to 20,000 Hz, and their hearing is most sensitive around the frequency range of the spoken human voice. As people get older, they start to lose the ability to hear the highest frequencies. In contrast, children and teenagers can be quite sensitive to high-energy, high-frequency sounds, which can make them feel dizzy or sick. Some security firms exploit this sensitivity by playing high-pitched sounds around private spaces, to keep teenagers away!

Loudness is measured with the decibel scale (dB). Acousticians (scientists who study sound and vibration) use a special decibel scale called A-weighting, which accounts for the way loudness changes depending on how high or low a frequency is. The scale spans from the ultra-quiet 0 dB, which is the lower limit of hearing, up to 120 or 140 dB, which is the level of sound that can cause pain (Figure 2). Sudden loud sounds, like high-speed hand dryers, might make people uncomfortable or jumpy [1]. This is the natural fight, flight, or freeze response kicking into action—it evolved to keep us safe from danger.

Figure 2

Examples of sounds, their measurements on the decibel (dB) scale, and how humans with typical hearing experience them.

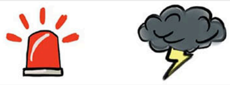
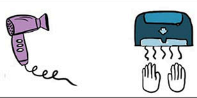
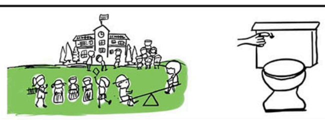
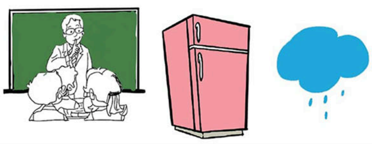
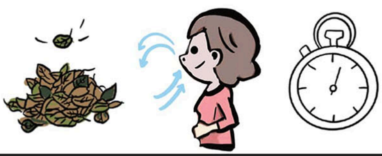
	140 dB and above	Threshold of pain
	130 dB	
	120 dB	Threshold of feeling
	110 dB	
	100 dB	Very Loud
	90 dB	Loud
	80 dB	Danger of noise-realted hearing damage over time
	70 dB	
	60 dB	Moderately loud
	50 dB	
	40 dB	
	30 dB	Quiet
	20 dB	
	10 dB	Very Quiet
	0 dB	Threshold of Audibility

Figure 2

DIFFERENT KINDS OF HEARING

As mentioned at the beginning of the article, auraldiversity describes that we all hear differently. For most of us, this difference is unimportant, but for some, the same sounds can be experienced very differently. Here are some interesting examples.

People with a condition called **diplacusis** may experience new frequencies coming from their ears—quite different from the frequencies coming from the outside world—creating a kind of "double hearing." Diplacusis can be especially challenging for musicians, who depend on reliably recognizing pitch.

If people have a condition called **hyperacusis**, their pain threshold can be much lower than 120 dB. Everyday sounds, such as the waves at the beach or bird song, can be intolerable.

Sometimes the cause of the sound can be the problem. People with **misophonia** can get very stressed and angry by human-made sounds, like other people eating crisps or snoring. In contrast, some people find these sorts of detailed sounds comforting. **ASMR (autonomous sensory meridian response)** is the name of a pleasant, tingling sensation that some people get from listening close-up to crunching, whispering, or tapping.

In busy environments, most people can identify individual voices among the crowd. We call this skill the cocktail party effect. Studies have shown that people have evolved to ignore most of the sounds around them. They do this until there is some significant change that catches their attention, such as overhearing someone mentioning their name [4]. But this is not the case for everyone. Autistic people can have very sensitive hearing, and they can become overwhelmed and anxious in noisy environments. However, some autistic people are particularly good at separating out the many sound signals that weave together to make the **soundscape**.

Films often try to recreate sounds the way the characters would hear them. In action movies, for example, the sound of an explosion is often followed by a combination of muffled sounds mixed with a loud, high-frequency pitch that quickly dies away. These scenes give viewers a feeling of what it is like to live with a condition called **tinnitus**. People with tinnitus may hear this sort of high-pitched tone constantly. This sound is not coming from anything outside of the person, but it can interfere with hearing normal sounds. We usually think of tinnitus as being a high-frequency, steady tone, but the tone can be of any frequency and can sound like a whooshing or throbbing.

Some people experience fascinating and unique connections between their senses, such as seeing sounds as having specific colors, or experiencing words as tastes or smells! Artists and musicians have

DIPLACUSIS

A sound with one pitch is perceived as having two distinct pitches, known as double hearing.

HYPERACUSIS

Very sensitive hearing with a low pain threshold where every day sounds can feel too loud.

MISOPHONIA

Sensitivity to specific sounds, commonly made by the mouth such as chewing, resulting in a negative emotional experience such as anger.

ASMR (AUTONOMOUS SENSORY MERIDIAN RESPONSE)

Pleasurable sensitivity to subtle sounds such as whispering.

SOUNDSCAPE

Our individual experience of the sounds of the environment.

TINNITUS

The experience of a phantom sound with no external cause, often a continuous high-pitched tone, but can also be low and throbbing or whooshing.

SYNESTHESIA

Unique and consistent connections that some people experience between the senses, such as sound and color, or words as taste or smell.

TEMPORARY THRESHOLD SHIFT

The dulling of hearing sensitivity for a short time after being exposed to loud sound.

embraced these cross-sensory mixes, called **synesthesia**, to produce highly original works. For Wassily Kandinsky, famous for his brightly colored abstract art canvases, his synesthesia was much more than a metaphor:

> Color is the keyboard, the eyes are the hammers, the soul is the piano with many strings. The artist is the hand which plays, touching one key or another, to cause vibrations in the soul [5].

Finally, if people are exposed to loud sounds, their hearing can adjust using what is called a **temporary threshold shift**. You might have noticed that your hearing becomes dulled if you listen to very loud music on headphones. Usually, the normal sensitivity returns once the sound has gone, but repeated exposure to sounds above 85 A-weighted dB, or exposure to a really loud blast of sound, can result in permanent hearing damage—so please take care of your ears!

CONCLUSION

This article has shown that hearing is not the same for everyone, and that our hearing will keep changing throughout our lives—this is called auraldiversity. To be sensitive to auraldiversity, we must learn about and have empathy for other people's hearing needs and celebrate the many forms of hearing that exist!

To conclude, it is important to remember how wonderful the sense of hearing can be. Here are the inspiring words of John M. Hull, who kept a diary of his experience and emotions as he became increasingly blind. This process made him feel very sad, but he opened up his world to a new reality by concentrating on his sense of hearing. Listening to the sound of the rain outside his kitchen window gave him a new perspective:

> ...the rain gives a sense of perspective and of actual relationships of one part of the world and another [...] I am presented with a totality, a world which speaks to me [6].

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YOUNG REVIEWERS

BROOKLYN, AGE: 11
Brooklyn likes to dance and hang out with her friends playing volleyball, ball hockey, and soccer.

ELISA, AGE: 13
Elisa is a young girl with a curious mind. She is very passionate about science, especially related to health. She is interested in research and would like to start getting involved in conducting her own explorations in high school. She hopes that, with her critical thinking, her love for health discoveries and her drive, she will be able to contribute to science through journal review.

JOAN, AGE: 15

In Joan's freetime, she can be found throwing a Frisbee with Tina, participating in DECA case studies, or simply enjoying a leisurely loiter on her school's property.

TINA, AGE: 15

Tina is a high school student. In her free time, you can find Tina either baking, working on her articles for the school newspaper, or playing Frisbee. Tina also enjoys going very fast down hills in the wintertime with two boards strapped to her feet (skiing).

AUTHORS

JOHN L. DREVER

John is passionate about all aspects of sound and hearing. He spends a lot of his time making sound recordings from the environment. He likes people to join him on soundwalks, to savor and learn about everyday soundscapes. Most recently, he collaborated with Rural recreation on the School of Insects, recreating insect stridulation sounds with rubbish from the recycle bin at Trumpington Park Primary School, Cambridge. He is Professor of Acoustic Ecology and Sound Art at Goldsmiths, University of London. When he is not working with sound, he is out in the countryside with his Italian water dog, hunting curious smells. *j.drever@gold.ac.uk

VINITA BHARAT

Vinita Bharat, Ph.D. holds the position of Assistant Director of Science Communication and Research Development Training in the Department of Pediatrics at Stanford University, USA. With her vast research experience, she has developed an appetite for communicating science to a broader audience. She runs an online platform called "Fuzzy Synapse" (http://fuzzysynapse.com) to bridge the gap between science and the world. She aims to make science accessible to everyone.

NEUROSCIENCE AND PSYCHOLOGY
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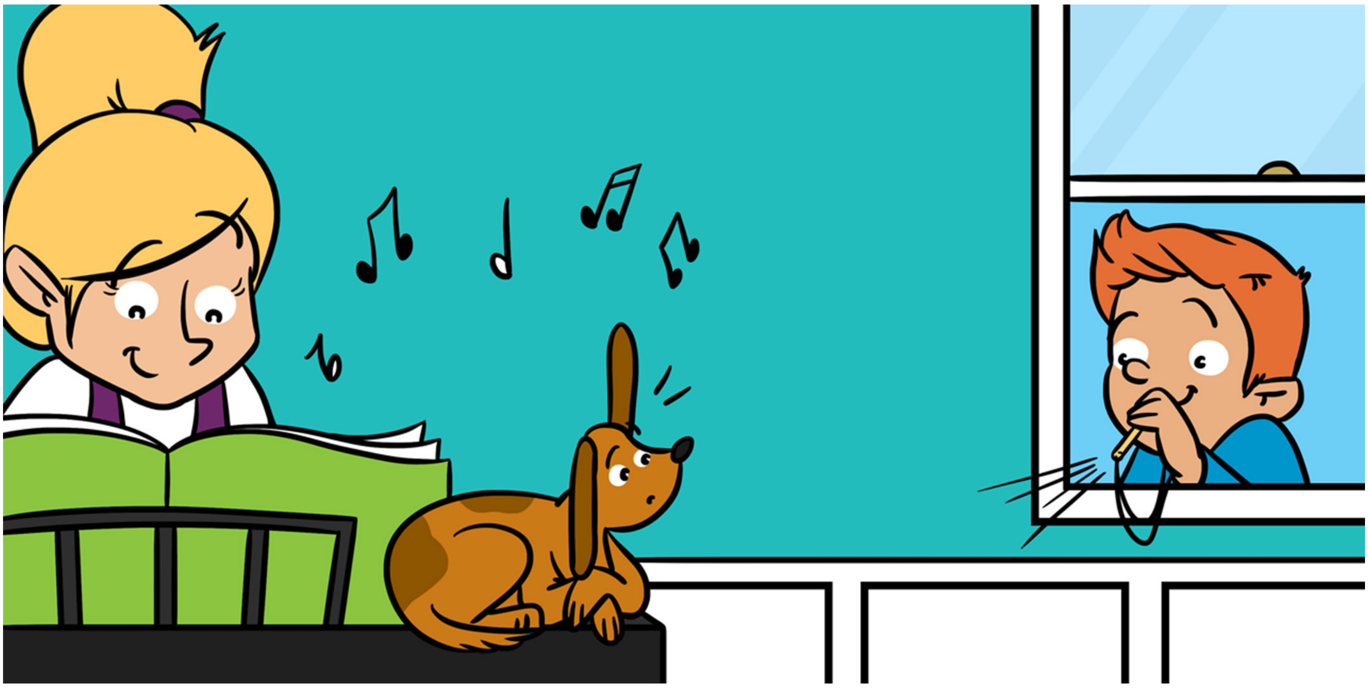

WHAT MAKES HUMAN HEARING SPECIAL?

Christian J. Sumner[1*], *Christopher Bergevin*[2], *Andrew J. Oxenham*[3,4] *and Christopher A. Shera*[5,6]

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[6] Department of Physics and Astronomy, University of Southern California, Los Angeles, CA, United States

YOUNG REVIEWERS:

ANAND
AGE: 14

EUNBI
AGE: 15

Humans and many other animals can hear a wide range of sounds. We can hear low and high notes and both quiet and loud sounds. We are also very good at telling the difference between sounds that are similar, like the speech sounds "argh" and "ah," and picking apart sounds that are mixed together, like when an orchestra is playing. But how do human hearing abilities compare to those of other animals? In this article, we discover how the inner ear determines hearing abilities. Many other mammals can hear very high notes that we cannot, and some can hear quiet sounds that we cannot. However, humans may be better than any other species at distinguishing similar sounds. We know this because, milliseconds after the sounds around us go into our ears, other sounds come *out*: sounds that are actually produced by those same ears!

INTRODUCTION

Our ears allow us to communicate with one another and to explore the world around us. They enable us to understand speech, hear music, and keep ourselves safe. They help other animals hunt, eat, and avoid being eaten. Most of the work of hearing is done inside our heads, in the inner ear, which contains the most intricate and rapidly moving parts in the body. Sound moves through the air as vibrations and is caught by the part of the ear we can see—the outer ear. The vibrations then move down the ear canal, through the middle ear, and into the inner ear. Here, the vibrations are converted into electrical signals that travel along nerves to the brain. The brain then works out what is making the sound, where the sound is coming from, and whether we need to do anything about it. Hearing these vibrations tells us that something out there is making a sound, but it also tells us a lot about the sound: is it an adult asking us if we have done our homework, or a friend asking whether we want a cookie? Most animals can hear some sounds that humans cannot hear, but it turns out that human hearing is remarkable in a different way.

SOUNDS PLAY THE "PIANO KEYBOARD" IN THE EAR

The sounds that travel as vibrations to the inner ear vary a lot—that is why they sound different! One important way that vibrations vary is in how fast the air is vibrating (Figure 1A). Imagine a piano keyboard (Figure 1B). The notes on the left side of the keyboard cause the strings inside the piano (and therefore the air around them) to vibrate slowly. To us, those notes sound "low." The notes on the right of the keyboard produce fast vibrations and sound "high" to us. We call the speed of these vibrations the **frequency** of the sound. We measure frequency in Hertz (abbreviated Hz), which is the number of vibrations per second. We are remarkably sensitive to the frequency of vibration, and we perceive different frequencies as different musical notes, or "pitches." How do we do that?

FREQUENCY

The rate of vibration of sound waves in the air. The number of times per second that air molecules complete a cycle of being squashed together, expand out, and back.

Incredibly, our ears sort out sounds from low to high, much like a piano keyboard! This important discovery was made almost 100 years ago by the Hungarian scientist Georg von Bekesy. It won him a Nobel Prize in 1961. The inner ear, or **cochlea**, is a spiral tube, shaped like a snail shell. Along the spiral is a **sound frequency map**, laid out like a piano keyboard. Figure 1C shows what the cochlear spiral would look like if it were pulled straight.

COCHLEA

The spiral shaped structure of the inner ear, where sounds are detected and organized according to frequency.

SOUND FREQUENCY MAP

Responses to sound are physically organized along the length of the cochlea, or across the surface of the brain, with orderly increasing sound frequency, like a graph (see Figure 2B).

Of course, the job of the cochlea is to *detect sounds*, not to make sounds like a piano. Instead of piano strings that *make* sounds of varying frequencies, the cochlea has locations along its spiral that *detect* vibrations of specific frequencies. Each location is most sensitive to a particular frequency and is connected to specific nerve fibers that send signals to the brain. The brain then works out the

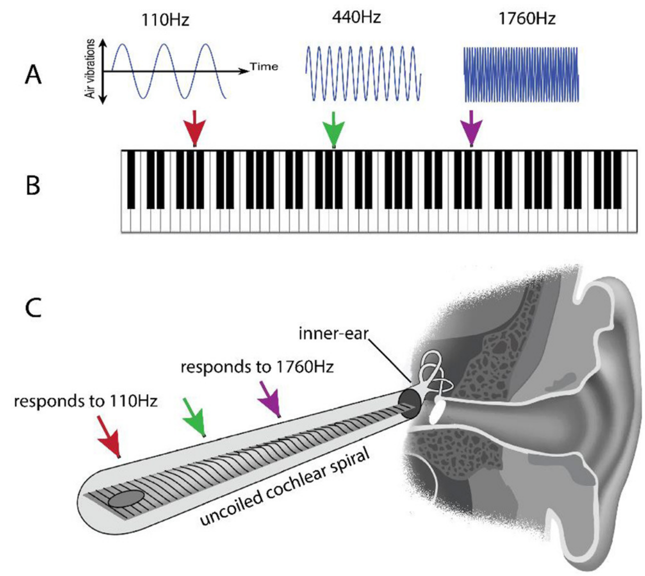

Figure 1

Figure 1

(A) Low-frequency sounds (left) make the air vibrate slower and high-frequency sounds (right) make the air vibrate faster. **(B)** These sound frequencies match with the musical notes on a piano keyboard. **(C)** Specific sound frequencies map to different locations in the inner ear (cochlea), shown in the cut-away of a human head. The cochlea is a spiral structure, like a snail shell, and specific frequencies cause nerve fibers to fire at specific points along the spiral. Here the cochlea is shown "uncoiled," to show the mapping of sound frequencies [image credit: **(C)** modified from a Wikipedia Creative Commons license image].

frequencies of the sounds we hear by determining which set of nerves is sending the signal.

The cochlea sends a constant chatter of electrical signals to the brain, telling us about the frequencies of sounds in the air as they change over time. The sound from an orchestra, or from human speech, is a complex combination of vibrations—lots of frequencies all at once! Somehow, we make sense of these complex sounds most of the time.

YOUR PETS HEAR SOUNDS THAT YOU CANNOT!

Comparing ourselves to other animals can help us better understand how hearing works. There are a few ways to measure how "good" our hearing is. One way is to look at the range of low to high sounds we can hear. Although humans cannot hear all frequencies, we can hear sounds both higher and lower in frequency than the notes on the piano. In fact, a keyboard covering the entire frequency range that a young human ear can hear (from 20 to 20,000 Hz, or roughly 10 octaves) would require about 120 keys instead of the 88 found on a grand piano (32 more—you would need long arms!). However, some animals can hear much higher frequencies than people can. Cats and dogs can hear frequencies twice as high as humans (about 40,000 Hz). Mice hear in the ultrasonic range (up to about 80,000 Hz) but cannot really hear frequencies below 1,000 Hz, which are the frequencies important for human speech and music (look back to Figure 1 to see how much of the piano keyboard that is).

We can also look at how sensitive our hearing is. This is a measure of how well we can hear very quiet sounds. People and other animals are best at hearing quiet sounds in the middle of their range, not at the upper or lower ends. We can use a graph called an **audiogram** to illustrate, for each frequency, how intense a sound must be to be heard (Figure 2A). The intensity of a sound is measured in decibels, where zero is approximately the quietest sound we can hear, and 100 can be uncomfortably loud. The audiograms show big differences in the frequencies that various animals can hear, but they also show that most animals are similarly sensitive to the quietest sounds. So, in terms of their sensitivity to quiet sounds and the frequency range of their hearing, humans are very ordinary: other animals can hear higher frequencies than we can, lower frequencies than we can, or quieter sounds than we can.

AUDIOGRAM

A graph showing for each frequency sound, how intense it must be to be heard at all. Sounds below this level are undetectable.

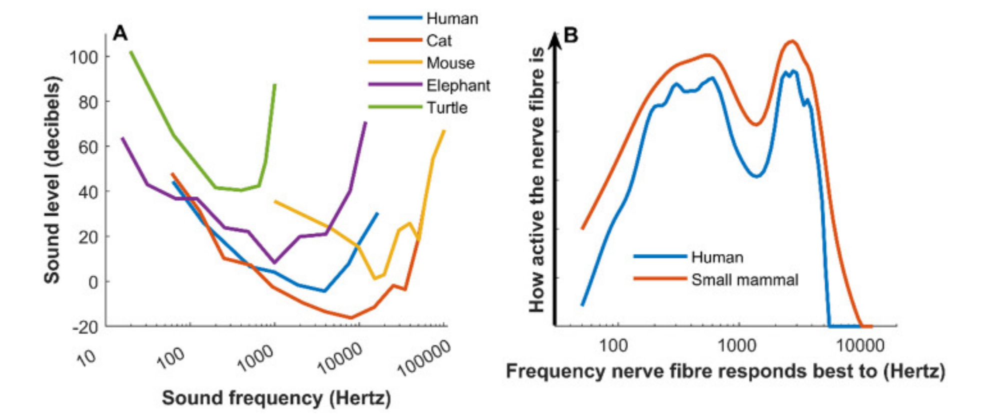

Figure 2

Figure 2

(A) Audiograms of various species show that humans fall squarely in the middle in terms of frequency range and sensitivity of hearing. Cats and mice, are more sensitive to higher frequencies. Cats are more sensitive to quiet sounds than humans are, while, elephants and turtles, are less sensitive overall (figure credit: [1]). **(B)** A computer simulation of activity in auditory nerve fibers in a small mammal and human, in response to the vowel sound "ee" as in "need." This graph shows that activity in human nerve fibers gives more detailed information about sounds than those of other mammals.

As you might expect, hearing is linked to an animal's size, its environment, and its communication needs. Human hearing is most sensitive to the frequencies present in human speech. Mice are small and produce high-pitched, squeaky sounds that we (thankfully) cannot hear. Not only can we not hear what mice are saying, but mice cannot hear much of what we are saying, either.

YOU MIGHT BE BETTER THAN YOUR PET AT TELLING SOUNDS APART

Being able to detect sounds tells us that *something* is out there, but we need to know more. Is it a bus that might run you over, or a friend asking you to play? Imagine your friend is talking with the television on in the background. Can you separate the words coming from the TV from the words your friend is speaking? How selective your hearing is to sounds of similar frequencies affects how easy or difficult it is to tell sounds apart. This **frequency selectivity** also affects how well you can distinguish between different sounds, like the words "go" and "slow."

FREQUENCY SELECTIVITY

Different parts of the cochlea respond to different frequencies. In a more selective cochlea, each part of the cochlea responds to a smaller range of frequencies.

Until recently, scientists thought that all mammals had similar frequency selectivity. It now seems that human hearing has better frequency selectivity than the hearing of most other species. Humans quite possibly hold the world record in this respect [2]! Figure 2B shows computer simulations of how scientists think the pattern of nerve activity varies between humans and small mammals when listening to the vowel sound "ee" (as in the second syllable of "cookie"). The human ear is selective enough to reveal important details in the sound, which shows up as small variations in the activity of nerve fibers. The more frequency selective an animal's hearing is, the more detailed the pattern of nerve activity when it hears the sound.

COMPARING SELECTIVITY IN DIFFERENT SPECIES

When testing hearing, it is difficult to measure humans and animals the same way. In humans, we can easily ask, "Is sound A different from sound B?" By varying the frequency of sounds, we can measure how accurately humans can distinguish various frequencies. It is not so easy to ask a mouse or a dog such questions! On the other hand, in animals we can directly monitor how the nerve fibers and brain cells respond to different sounds. This usually involves complex brain surgery, which makes it unsuitable for use in people.

Because the measurement methods for selectivity are different for humans and animals, it can be challenging to compare results across species. When we see differences, we must ask whether they are *real* differences in hearing or just a result of using different measurement techniques. It is possible to train animals to perform hearing tests similar to those used on humans, but it is very difficult and timing consuming. Your dog might sit down on command but imagine the difficulty of training it to sit or give you a paw when it hears two adjacent notes on the piano! Recording from the nerves of the inner ear may one day be possible in humans, but it is very difficult and has not yet been achieved.

A solution to this dilemma came from a rather surprising technique. In 1978, a scientist named David Kemp discovered that sounds do not just go *into* the ear, they come *out* as well! When a sound enters the inner ear, the sensory cells of the cochlea pick up the vibrations and then add more vibrations of their own, which bounce back out of the ear like an echo. These are called **otoacoustic emissions** and they are often used to test the hearing of newborn babies. Otoacoustic emissions can also be used to probe the frequency selectivity of the cochlea, although it involves some rather complicated mathematics. In a nutshell, the longer it takes a sound to come back out of the ear, the more frequency selective the cochlea is, and therefore the more different are the patterns of nerve firings in response to different frequencies.

OTOACOUSTIC EMISSIONS

Sounds that are produced by the inner ear vibrating. These can be spontaneous or produced in response to sound. Vibrations in the inner ear result in sound at the outer ear.

With this in mind, some of our group played tones of various frequencies to the ears of different animals and recorded the otoacoustic emissions (Figure 3) [3]. The measurements suggested that human ears are *more* frequency selective than the ears of other animals. More recently, we carefully explored whether measuring otoacoustic emissions is accurate, by painstakingly making all the different types of measurements we have talked about here (perception, otoacoustic emissions, and nerve recordings) in a single species: the ferret [4]. Ferrets are relatively easy to train and have a hearing range similar to that of humans. These measurements confirmed that otoacoustic emissions *do* show how selective the inner ear is to sounds of various frequencies. Most scientists now agree that, while human ears may not hear the high frequencies audible to some of our mammalian relatives, we have better frequency selectivity than most of those animals.

Figure 3

Measurements from the sounds (otoacoustic emissions) coming *out* of the ears of various species. The y-axis shows how long it takes after a sound is played into the ear before the response comes out. The longer it takes, the more selectively each nerve fiber responds to a particular range of frequencies (figure credit: [3]).

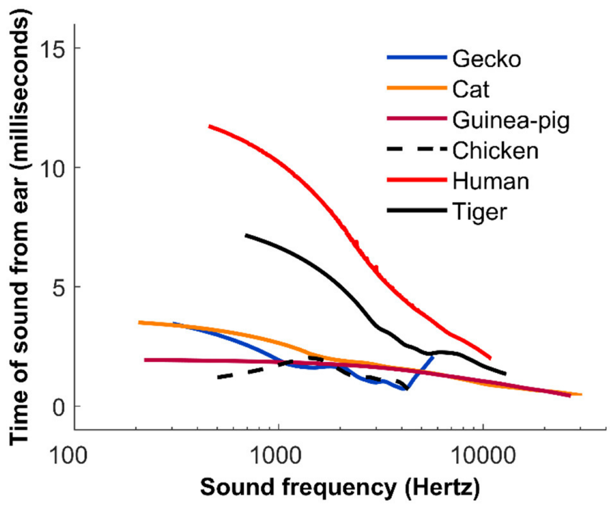

Figure 3

WHY SHARP HEARING IN HUMANS?

Although many species can hear sounds that we cannot, it certainly looks like humans are better at separating sounds and telling similar sounds apart than other species are. Perhaps this ability is related to our amazing skills in communicating. Outstanding frequency selectivity may well have played a role in human evolution and the development of language and communication [see this Frontiers for Young Minds article [5], and this one [6], for examples of the subtle ways we use and recognize speech]. However, nothing is ever totally simple. Surprisingly, humans can still understand speech even when the sounds have been computer modified to remove most of the frequency differences [7]. Also, a few species, such as tigers, do not speak like we do but appear to have hearing that is almost as selective as that of humans (Figure 3). The next challenge is to figure out *why* human hearing is so selective.

To sum up, we have known for a long time that in terms of range of frequencies and sensitivity to quiet sounds, a human would not win the top prize in a "spot-the-sound" competition against other animals. There would likely be another animal that could spot a quiet sound more easily than us! However, we now know that human hearing is more frequency selective than other animals. So perhaps we could win the inter-species "spot-the-difference-between-sounds" competition!

ORIGINAL SOURCE ARTICLE

Sumner, C. J., Wells, T., Bergevin, C., Sollini, J., Palmer, A. R., Oxehham, A. J., et al. 2018. Convergent measures of mammalian cochlear tuning confirm sharper human tuning. *Proc. Natl. Acad. Sci. U. S. A.* 115:11322–6. doi: 10.1073/pnas.1810766115

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YOUNG REVIEWERS

ANAND, AGE: 14

An avid learner of science and history, Anand enjoys biology and health science. His specific areas of interest are neuroscience and neurosurgery. Outside of academics, Anand's hobbies include participating in academic competitions and learning more about roller coasters. He is a black belt in Tang So Do karate.

EUNBI, AGE: 15

My name is Eunbi and I am currently a 10th grader at Lowell High School in San Francisco, California. During the pandemic, I further expanded on my passion for science. The wonders in the galaxy that science handles fuels my fascination toward all fields and research. I aspire to continue my journey through education and experiences, with my strong belief that even small discoveries could influence the future of this world.

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Christian J. Sumner is an associate professor in auditory neuroscience at the Nottingham Trent University. He has a background in computer science, and so views the brain as a big computer—and wants to understand the program for how we hear! He has wide interests across hearing, from how the brain separates out simultaneous sounds (such as instruments in an orchestra) or how single neurons in the brain process sound, to how hearing changes as we age. His career choice stemmed from an interest in music, and he lacked most of the necessary characteristics to become a rock star.*christian.sumner@ntu.ac.uk

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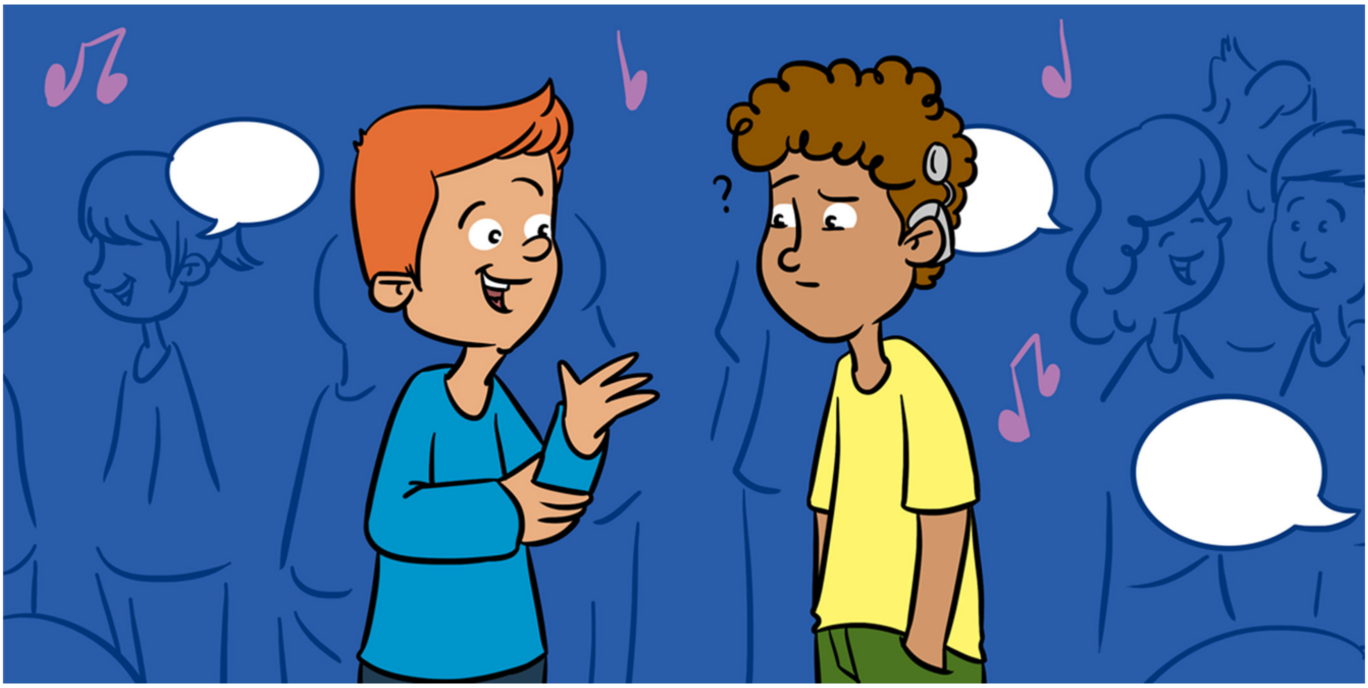

I CAN'T HEAR MYSELF THINK! HOW THE BRAIN DEALS WITH TALKING IN NOISY ENVIRONMENTS

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YOUNG REVIEWER:

ARITRO
AGE: 13

Imagine you are at party with loud music playing. What would it be like trying to speak to your friend in all that noise? Scientists call background noise like this "masking sound" because it covers up other sounds, in two ways. The background sound might be so loud that it blocks out other noises, or it might contain information that is distracting. Maybe it is your favorite song and you cannot help singing along! Which of these do you think affects you most when you are trying to talk? We decided to find out by putting people in a brain scanner and asking them to talk while we played various noises in the background. We found that the brain cares most about sounds that contain lots of information, even if they do not block out other noises very well. So, maybe being able to hear yourself is not as important as we thought!

MASKING: THE PROBLEM WITH TALKING IN NOISE

Most of us have conversations with other people every day, in all kinds of places—at home, in the street, at a party, or in the playground, for example. If you are at home in a quiet room, it is pretty easy to concentrate on what you are saying. But what if you are standing on a busy street, or meeting a friend at a fairground? Holding a conversation in a very loud place can be tricky. But what is it that makes such a conversation difficult?

Scientists who study speech have identified two ways that background sounds make it harder to hear and talk to other people. When one sound covers up another, we call this **masking**. Masking potential is how likely one sound is to mask, or cover up, another. The first type of masking potential happens when the background sound physically covers up your voice. This is called **energetic masking potential** because it is the ***energy*** of the sound wave that covers up your voice. "Energy" could include how loud the sound is (volume) or how high or low it is (pitch). The louder the sound, or the closer it is in pitch to the sound it is masking, the harder it is to pick the two apart.

The second type of masking potential happens when the background sound contains information that may distract you. This is called **informational masking potential** because it is the ***information*** in the background sound that covers up the other sound. "Information" can mean words or other things that have meaning to you, like sirens or music. Your brain must spend time figuring out what is relevant and what is not. All sounds have a little bit of both types of masking potential.

Imagine you are at a fairground and just got off the roller coaster. You spot your friend at the candyfloss stall and go over to tell them all about your ride. But the candyfloss stall is blasting out instrumental music, making it hard to hear yourself talking. This is mostly energetic masking, with a little bit of informational masking from the pattern of the music. Now, imagine you hear an announcement on a loudspeaker saying, "FREE RIDES ON THE TWISTER!" You would probably stop talking to listen to the announcement, then rush over to the twister for your ride. This is mostly informational masking, with a little bit of energetic masking from the loudness and pitch of the announcement.

Scientists have done a lot of research into how we *listen* to speech when there is background noise, so we know that energetic and informational masking work in different ways and are processed differently by the brain [1]. However, we do not know as much about what happens when we are trying to *talk* in a noisy environment. This work could help us understand how our brains control our voices, which might also help us figure out why some people have problems with their speech.

MASKER

A sound that covers up what you are trying to listen to.

ENERGETIC MASKING POTENTIAL

How good a sound is at blocking out other sounds.

ENERGY

Physical properties, like pitch and loudness, that block out the thing you are trying to listen to.

INFORMATIONAL MASKING POTENTIAL

How good a sound is at distracting you from other sounds.

INFORMATION

Non-physical properties, like meaning, that may distract you from the thing you are trying to listen to.

Figure 1

Surface view of the left side of the brain, with the temporal lobe highlighted in light orange and the posterior superior temporal gyrus highlighted in dark orange.

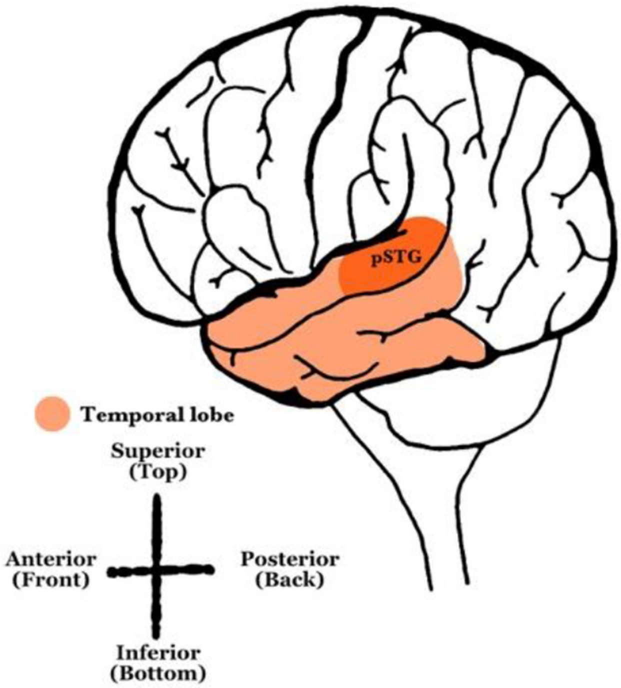

Figure 1

POSTERIOR SUPERIOR TEMPORAL GYRUS (PSTG)

The area at the back (*posterior*) of the superior temporal gyrus. The part of the temporal lobe that is on the outside (*gyrus*) near the top (*superior*) of the lobe.

HOW DOES THE BRAIN HELP US TALK IN NOISY ENVIRONMENTS?

We looked at a part of the brain called the **posterior superior temporal gyrus** (**pSTG**). This area is found in both the left and right sides of the brain (Figure 1).

There are two things scientists think the pSTG might be doing when we talk in a noisy environment. First, it might be listening to your own voice to see if you are being clear enough. If you make a mistake, or if you cannot hear yourself properly over the noise, the pSTG will register an "error" and try to change your voice to fix it. This is what seems to happen when people talk in noise with low information content, such as traffic noise. As the noise gets louder and it gets harder to hear yourself, the pSTG gets more active [2]. The second thing the pSTG might be doing is keeping track of what is going on in the background, in case there is information we can use.

We know that the pSTG is activated when someone is trying to listen to one person while others are also talking, and we also know that we pay attention to what is going on in the background when we are talking. It is easier to talk when breaks in the background noise happen at regular times [3]. Someone who wants to speak will often wait until other people have stopped talking. In our fairground example, you would probably stop talking to your friend until the loudspeaker had finished.

While some studies look at how distracting speech can be, most have looked at how people react to "white noise," similar to the sound of an airplane passing overhead. These studies have concluded that we do not pay attention to the content of background noise when we are trying to talk. Instead, we focus on how well we can hear ourselves and use that information to change our voices [4]. It makes sense that we would mostly ignore background noise when there is little information in it. We wondered if this is still true when the background noise consists of something potentially interesting, like speech. In that case, do we focus on listening to ourselves, or to what is going on in the background?

TESTING WHAT THE BRAIN DOES WHEN WE SPEAK IN NOISE

A brain scanner measures how much blood is traveling to various parts of the brain. The harder a brain area is working, the more blood it needs. The results are shown on a screen as a picture, in which brightly colored areas are the most active.

We asked people to lie in a brain scanner and read sentences aloud while we played sounds with various levels of energetic and informational masking. There were four types of sounds, starting with recordings of people talking and getting gradually less speech-like and more like white noise. We then asked the participants to read sentences silently to themselves while listening to the sounds. We compared the silent reading condition to reading aloud with the various maskers, to make sure that we were measuring changes related to talking in each condition, not just to hearing various kinds of noise. We wanted to know how active the pSTG was when people spoke in each kind of background sound.

If people focus mainly on their *own speech* when talking in noise, then how well we can hear ourselves will be the most important thing when trying to speak in a noisy place. In this case, we would expect the pSTG to register more "errors" when background noise had more energetic content. In other words, the more effective the background noise is at blocking out the speaker's voice, the harder the pSTG must work and the more activation we will see. But if people mainly focus on what is going on around them when trying to speak in a noisy place, we would expect the pSTG to be most active when background noise has more informational masking. In other words, the more interested we are in the background noise, the harder the pSTG must work and the more activation we will see.

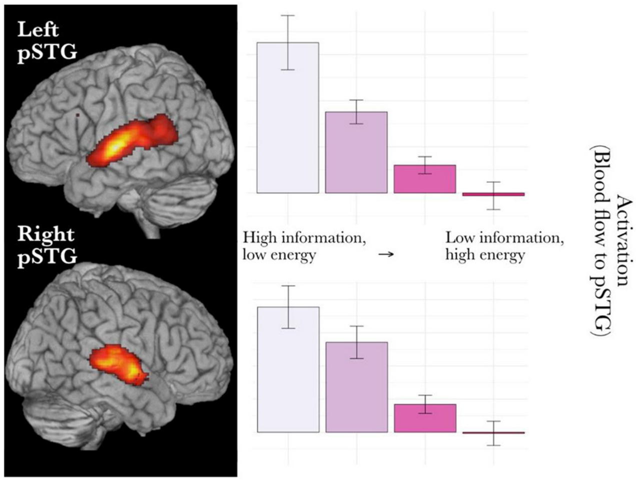

Figure 2

Figure 2

Areas that responded more to talking in noise (compared to just listening). The bar charts show the amount of blood flow to those brain areas when people spoke in each of the four maskers. The pSTG on both sides of the brain was most active when people talked in sounds that had high information and low energy (like speech) and was least active when they spoke in sounds that had high energy and low information (like white noise).

WHICH MATTERS MORE?

Based on findings from previous brain scanning studies, we expected a strong response in the pSTG when people talked in noise with more energetic masking potential. Instead, we found something that surprised us (Figure 2). Although the pSTG was active when people spoke in maskers with high energetic masking potential, this was only a small response. The response was much bigger when people tried to talk in maskers with high *information* content. In fact, the more information there was in the background, the more active the pSTG was. In other words, our brains work harder to concentrate on talking when background noise contains information that we are interested in. Our brains are less bothered by how much the background noise covers up our voices.

It could be that the brain mistakes speech-like background noise for our own voice, causing the brain to register an "error." However, there is not much evidence to suggest that we cannot tell our own voices apart from those in the background. We think it is more likely that this extra brain activity happens because people are monitoring the background noise for relevant information. This does not mean that the brain completely ignores energetic masking when we are speaking. Our participants *did* speak more loudly when we played sounds with more energetic masking potential, showing that our brains *do* monitor how well others might hear our voices. But overall, we found that informational masking made the most difference to brain responses, suggesting that speech-like sounds in the background were the most distracting. We think that the brain response to informational masking is so strong that it drowns out any response to the energetic content of sounds.

In the future, we would like to look at our data using more sensitive analysis techniques, to see if we can find brain areas that care more about energetic masking. While more studies and analysis will help us better understand our results, we now know that the ability to hear yourself when talking in noisy environments is not as important as we once thought! Understanding how humans talk is essential to figuring out how why some people have difficulty with speech. So this is an exciting result that tells us more about ourselves, and may be able to help some people in the future.

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YOUNG REVIEWER

ARITRO, AGE: 13

I have an keen interest in geography and how it is applied to drawing maps of landscapes and roadways. I love playing music and play the viola in the youth philharmonic. At school, I compete in the Vex IQ robotics competition and MathCounts math logic competition. While outside, I enjoy playing tennis and kayaking.

AUTHOR

SOPHIE MEEKINGS

Dr. Sophie Meekings is a postdoctoral researcher at Newcastle University and a visiting researcher at University College London. She is interested in questions like:

- How do we control our voices?
- How does your voice relate to your sense of identity?
- How are these things different in people who have neurological conditions that affect their speech, like stammering, stroke, or Tourette syndrome?

Her research attempts to address these questions by looking at how people change their voices in different situations, how this is related to brain activation, and how people feel about voices that sound different to theirs. *sophie.meekings@york.ac.uk

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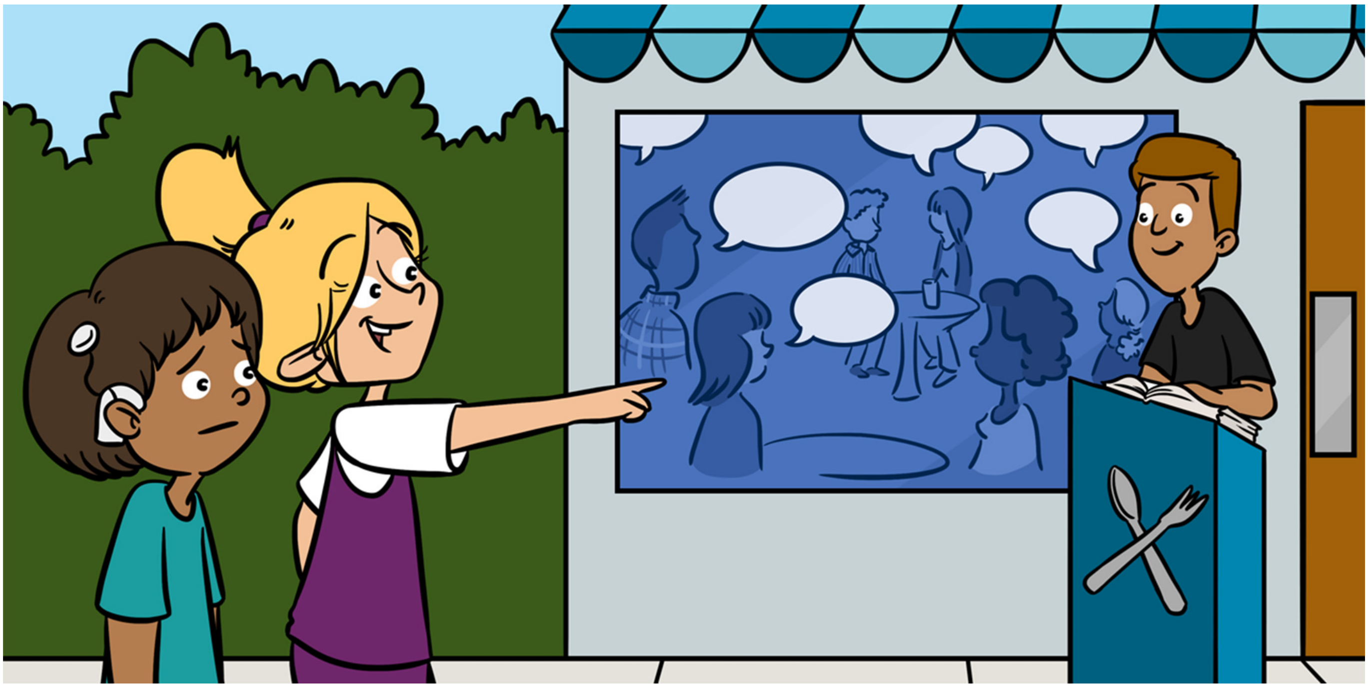

HELPING PEOPLE HEAR BETTER WITH "SMART" HEARING DEVICES

Tobias Goehring [1*] ***and Jessica Monaghan*** [2]

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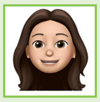

CHAITANYA
AGE: 16

THE SCHOOL FOR SCIENCE AND MATH AT VANDERBILT
AGES: 13–14

Millions of people around the world have difficulty hearing. Hearing aids and cochlear implants help people hear better, especially in quiet places. Unfortunately, these devices do not always help in noisy situations like busy classrooms or restaurants. This means that a person with hearing loss may struggle to follow a conversation with friends or family and may avoid going out. We used methods from the field of artificial intelligence to develop "smart" hearing aids and cochlear implants that can get rid of background noise. We play many different sounds into a computer program, which learns to pick out the speech sounds and filter out unwanted background noises. Once the computer program has been trained, it is then tested on new examples of noisy speech and can be incorporated into hearing aids or cochlear implants. These "smart" approaches can help people with hearing loss understand speech better in noisy situations.

HEARING AND HEARING LOSS

Sound is created when objects vibrate. These vibrations travel through the air as sound waves. When sound waves reach our ears, they travel from the outer ear, down a tube called the ear canal, then they vibrate the eardrum and tiny bones in the middle ear, to reach the inner ear or **cochlea**. In the cochlea, thousands of sensory hair cells translate sound vibrations into electrical signals that then travel along nerves to the brain. The brain receives these signals and perceives them as speech, music, or other sounds.

COCHLEA

The spiral-shaped part of the inner ear that contains the sensory organ of hearing.

Around one in five people in the world has some degree of hearing loss. This adds up to around 1.5 billion people, so hearing loss is a huge problem with societal, health, and economic impact. The World Health Organization predicts numbers will rise to one in four people by 2050. Currently, 400,000,000 people have hearing loss serious enough to require hearing aids. There are many different reasons why hearing loss occurs, for example getting older, listening to too much very loud music, or due to illnesses or medicines that harm the ears. The most common type of hearing loss affects important processes in the inner ear that convert sound waves into nerve signals and this can cause difficulties understanding speech.

DEVICES FOR PEOPLE WITH HEARING LOSS

Certain devices can help people with hearing loss. Depending on the amount of hearing loss, two main types of hearing devices are available. For most forms of hearing loss, **acoustic hearing aids** work well. These have a tiny microphone that changes sound into an electrical signal that is sent to a **digital signal processor**—a device that can very quickly modify sounds and amplify them (make them louder), to make sounds easier for the person to hear (Figure 1). The louder, modified sound is carefully optimized to suit the specific needs of the person before it is played into the person's ear using a small loudspeaker positioned by the ear canal.

ACOUSTIC HEARING AIDS

A small electro-acoustic device to let people hear better.

DIGITAL SIGNAL PROCESSOR

A small computer chip used in many electronic devices to process signals such as speech, sound, video, or other digital data.

If hearing loss is severe, acoustic hearing aids may not provide enough amplification. In these cases, **cochlear implants** can be used. Cochlear implants also have an external microphone and a digital signal processor, but they also have an internal part, consisting of tiny electrodes, that is implanted inside a person's cochlea by a surgeon. The internal part of the cochlear implant turns the sound information into electrical signals (Figure 1). The sound is split into different **frequencies**, ranging from low to high tones. Higher tones stimulate electrodes at the beginning of the cochlea and lower tones stimulate electrodes further into the cochlea. It is important to match the electrical signal to the location of the nerves along the cochlea so that the person can hear different tones and hear them in the correct order, from low to high.

COCHLEAR IMPLANTS

A small electronic device to let people hear via electrical stimulation of the auditory nerve in the cochlea.

FREQUENCIES

The rate at which a sound wave vibrates. Lower frequencies (slower vibrations) are heard as lower tones (like a man's voice); higher frequencies are heard as higher tones (like a child's voice).

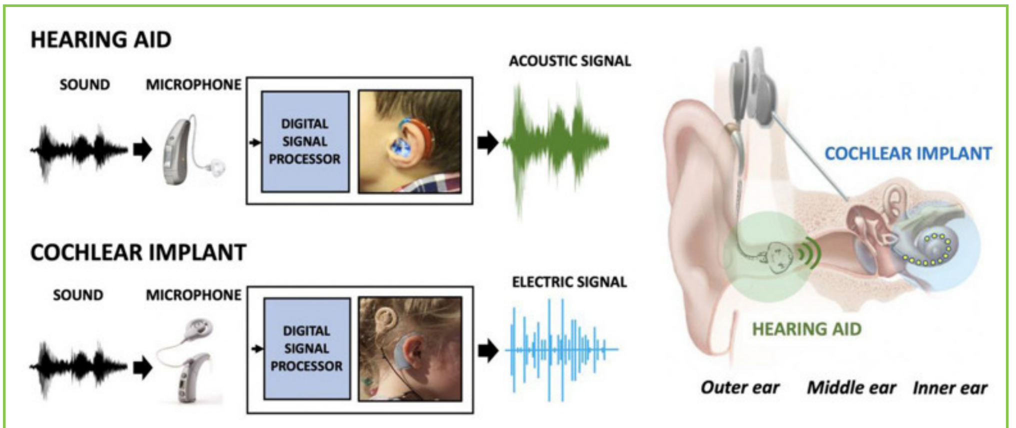

Figure 1

Figure 1

Both hearing aids and cochlear implants record sound with a microphone and process it with a digital signal processor, to optimize the sound for the person's hearing loss. The hearing aid then uses a small loudspeaker in the ear canal to present the amplified sound as an acoustic signal (green). The cochlear implant uses tiny electrodes inside the cochlea to present the sound as an electric signal (blue). Depending on the degree and type of hearing loss, either a hearing aid or a cochlear implant (or a combination of both) can be used to help a person hear better.

PEOPLE WITH HEARING LOSS STRUGGLE TO HEAR WELL IN NOISY PLACES

Even when using a hearing aid or a cochlear implant, it is often much more difficult for people to understand speech in noisy situations such as a busy classroom, workplace or restaurant. This means that a person with hearing loss might struggle to understand what friends or family are saying to them and may not want to take part in conversations.

Difficulty hearing speech happens because hearing aids and cochlear implants cannot recover the fine details of sound that are needed to understand speech, so the sound information that reaches the brain is not as detailed as it needs to be. People with hearing devices may still find it difficult to hear pitch (how high or low a tone is) or whether a person's voice rises at the end of a sentence to form a question. Some people with hearing aids or cochlear implants also find it hard to tell different sounds apart. This makes it particularly difficult for them to follow and to understand speech correctly when the background is noisy. Even the best hearing aids and cochlear implants cannot get rid of background noise in real-life situations.

SMART COMPUTER PROGRAMS THAT LEARN FROM THEIR MISTAKES

ALGORITHMS

A set of rules to be followed for a process or operation, for example by a computer.

We are developing smart **algorithms** (computer programs) that can learn to make speech in noisy situations clearer and easier to understand. An algorithm is a set of rules followed by a computer, to perform a task or to solve a problem.

In previous research, speech was separated from noisy background sounds based on fixed rules, similar to a recipe. These rules had to be followed strictly by the digital signal processor in the hearing device.

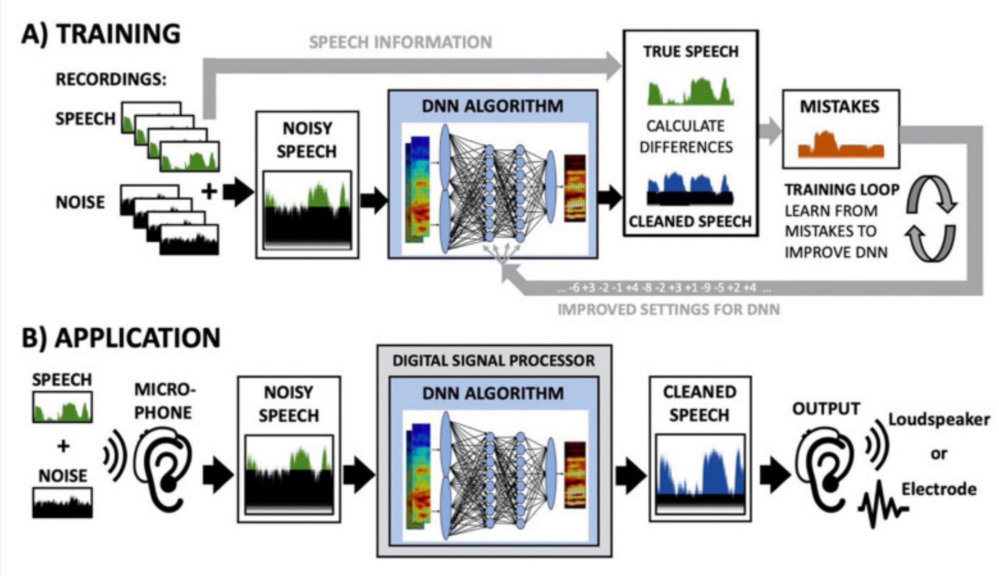

Figure 2

Figure 2

(A) Many examples of speech and noise recordings are mixed together to get noisy speech. The DNN algorithm then tries to clean up the speech, which is compared against the true speech to calculate the algorithm's mistakes. Over many thousands of training loops, the DNN algorithm is adjusted step-by-step, based on learning from its mistakes, to get better at cleaning up the noisy speech. **(B)** After training is complete, the DNN algorithm can then be used in the digital signal processor of hearing aids or cochlear implants.

ARTIFICIAL INTELLIGENCE

Methods to enable computers and algorithms to perform some intellectual tasks such as decision making, problem solving, communication, or perception.

ARTIFICIAL DEEP NEURAL NETWORK

A computer algorithm inspired by the neural networks found in biological brains.

This method only works for background sounds that are very different from speech. But in the real world, background noise often contains speech-like sounds, such as people chatting. For these situations, fixed rules do not work well. In the field of **artificial intelligence**, the goal is to build machines or computer programs that can learn from data. Researchers have begun to use these techniques to improve hearing aids and cochlear implants.

The specific algorithm we used is called an **artificial deep neural network** (DNN), which simulates the way the human brain learns. Because the human brain is very complex and powerful, DNN algorithms are not nearly as smart, but they are still much more powerful than older algorithms built on fixed rules. DNNs learn a set of rules depending on the task. In our research, we train DNNs to learn how to improve how speech sounds when there is background noise. To do this, we record lots of people saying a range of sentences. We then add realistic background noise, recorded in a busy restaurant or beside a busy road, and we play the mixed sounds to the DNN. We do not provide a set of rules to the DNN, but we tell the DNN which sounds make up the speech and which sounds make up the noise to get rid of. We basically teach the DNN step-by-step how to perform this task (Figure 2A).

At the beginning of the training, the DNN makes a lot of mistakes because it has no experience in cleaning up speech signals. But these mistakes are important and valuable, because we can use them to teach the DNN how to make decisions about which sounds to keep and which sounds to filter out. During training, the DNN builds its own set of rules, by adjusting the settings of its parameters step-by-step. By listening to thousands or even millions of examples of many kinds of noisy speech mixes, the DNN's parameters are optimized to reduce the

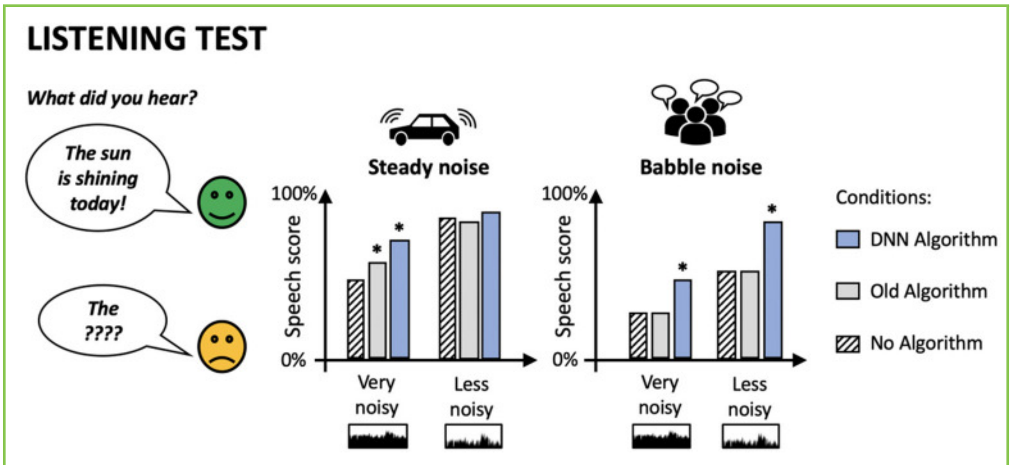

Figure 3

Figure 3

People with hearing devices listened to noisy sentences that were cleaned up by the DNN algorithm, an old, fixed-rules, algorithm, or no algorithm. The more words that were understood correctly, the higher the speech score. Speech was mixed with either steady background noise or "babble" noise, like many people talking. Very noisy and less noisy situations were tested. Asterisks mean that the result is probably real—not based on luck. Results show that the DNN algorithm improved speech scores more than the old algorithm did, especially with babble noise.

number of mistakes it makes when cleaning up speech. Once training is complete, the DNN algorithm can be added to the digital signal processors of hearing aids and cochlear implants (Figure 2B).

In our research, we trained DNNs to improve noisy speech as much as possible and then performed listening tests to study how well the algorithm worked for people that use hearing aids [1] and cochlear implants [2, 3]. We measured how easy it was for our test subjects to hear the words in sentences, by counting the words they understand correctly, and we measured how pleasant the sounds were to hear, by asking them for their opinions.

RESULTS FROM THE LISTENING TESTS

We found that the DNNs improved the understandability of speech by up to 14% for people using hearing aids (Figure 3) [1] and by about 30–40% for people using cochlear implants [2, 3]. The DNN algorithm also worked better than the fixed-rules algorithms used in the past.

Even a small amount of background noise causes difficulties for people with cochlear implants. So, the DNN algorithms we are building sometimes work better for people with cochlear implants than those with hearing aids because the algorithms do not need to filter out as much noise to make a difference. The DNN algorithms also work better if there is less noise to remove. Overall, the DNN algorithms perform well when speech is at least as loud as background noise, but they start to struggle when the noise is louder than the speech. DNNs successfully improved speech scores even when there were many people talking in the background, which is a clear improvement over previous algorithms, which did not work well in those cases.

We also found that it is much easier for the DNN algorithm to improve speech signals when it has been trained on a particular voice or a specific background noise; it does not perform as well for completely different speech and noise recordings that were not part of the training. This can be seen as a strength of DNN algorithms, because we can fine-tune them to work better with specific voices or noises. However, it can also be seen as a weakness because the DNN algorithm may become too specialized and then would not help much in other listening situations, for example with other voices.

SUMMARY

For many people who have hearing aids or cochlear implants, listening to speech in noisy situations can be difficult and tiring. We are building smart algorithms based on artificial intelligence techniques that can be used to improve future hearing aids and cochlear implants, particularly to help get rid of background noises. The algorithms use artificial DNNs that become smarter by learning from their own mistakes during training with many thousands of noisy speech examples. These algorithms are then used to clean up speech recordings before presenting those recordings to people with hearing loss and measuring their speech scores. Our results showed DNNs resulted in improvements in how well people could hear speech in the presence of noise, and how much they liked the sound of that speech. These results, along with other studies [4, 5], show that there is great potential to improve hearing aids and cochlear implants. With "smart" technology and algorithms such as DNNs, we can help people with hearing loss to hear speech better and thus help to make their communication easier.

FUNDING

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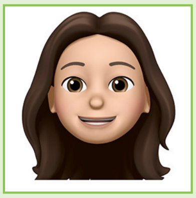
CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS



CHAITANYA, AGE: 16
I am a year 10 student with a passion for environmental sustainability and neuroscience. I have participated in STEM related programs and short film competitions. I enjoy rowing, dancing and badminton. This year, I am the year level debating executive at my school.

THE SCHOOL FOR SCIENCE AND MATH AT VANDERBILT, AGES: 13–14
We are a class of students from all over Nashville who come together once per week at Vanderbilt to learn more about science, technology, engineering and mathematics. We conduct experiments in our classroom and in labs on campus!

AUTHORS

TOBIAS GOEHRING

I am a senior research scientist at the MRC Cognition and Brain Sciences Unit, University of Cambridge. My goal is to improve hearing by people with hearing loss. Since I learned about cochlear implants, I am fascinated how technology can be used for this. I first got interested in sound and auditory perception through playing electric guitar and making music. I then studied electrical engineering and worked as acoustic engineer on cars before starting research on hearing during my Ph.D.

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JESSICA MONAGHAN

I am a senior research scientist at the National Acoustic Laboratories in Sydney, Australia. I am interested in the amazing ways our brain makes sense of speech in difficult situations. I really enjoy coming up with new ways that we can use technology and especially machine learning to test people's hearing or to help people hear better. When I am not researching, I enjoy snorkeling and spending time with my family.

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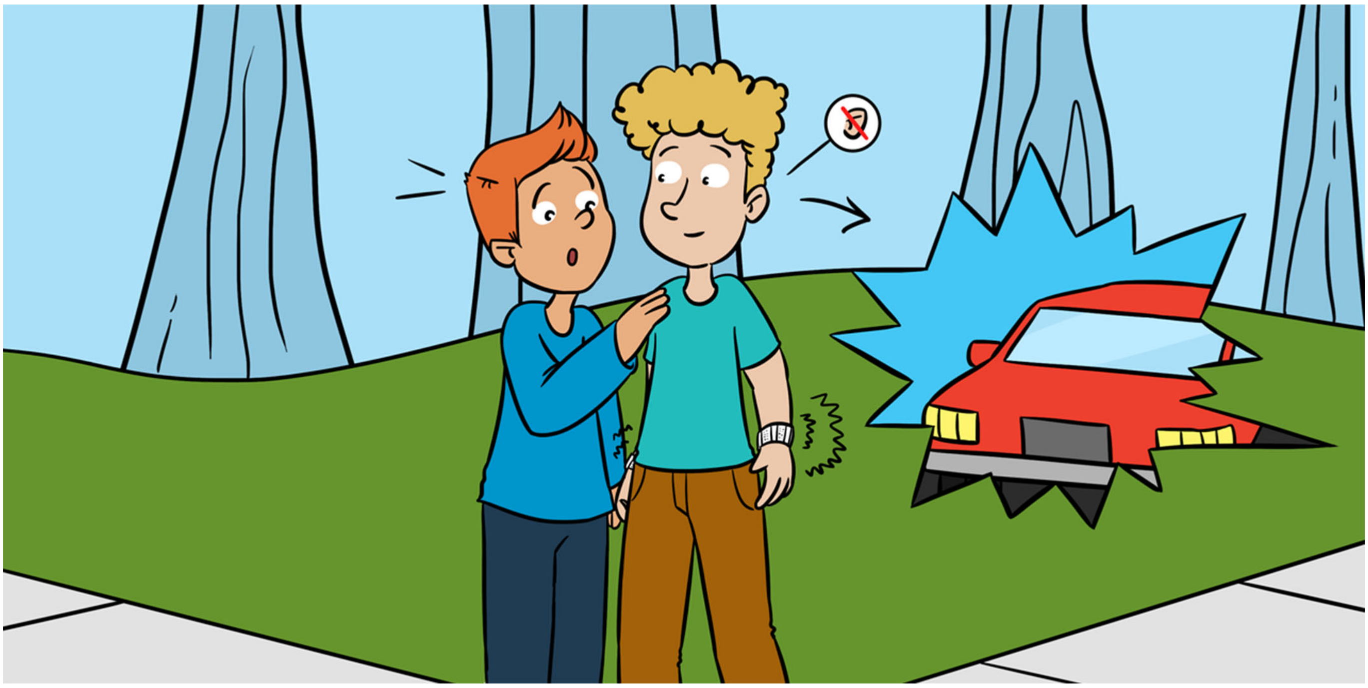

LISTEN WITH YOUR WRISTS

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YOUNG REVIEWERS:

ELLA
AGE: 11

LOTTE
AGE: 13

Most of us have five senses that our brains use to create a model of the world around us. We see, hear, smell, taste, and touch our way around. If one of your senses is not working properly, your brain fills in the gaps by paying more attention to the other senses. However, your other senses cannot always fill in the gaps. If your ears are not working, your eyes alone may not be able to tell your brain that an out-of-control car is screeching toward you! But what if we could help the brain fill in the gaps by purposefully sending the missing information through another sense? What if you could "hear" where a sound is through your sense of touch? This article will explain how people were able to do just that, using wristbands that converted sound into vibration.

A BROKEN MODEL OF THE WORLD

In your head, you carry around a model of the world. This model has been built using all the information your brain has gathered from your senses. It tells you where things are, which things are dangerous or desirable, who is shy, and who likes to show off. The model is continuously updated and improved by new information that pours in from your eyes, ears, nose, and mouth, and from sensors all around your body monitoring touch and temperature. Your brain loves information and is always hungrily searching for more.

But what happens when the information stops flowing from a sense because it is too dark to see or too noisy to hear? In this case, the brain fills in the missing information by focusing harder on other senses. For example, if you are trying to follow a conversation but you cannot get enough information from your ears, you focus more on the movement of the speaker's lips. If you are walking down a dark street and think you glimpse someone lurking in the shadows, you listen all the more closely for footsteps.

Unfortunately, your brain cannot always get the information it needs by focusing harder on other senses. If you are in a noisy hall, where clattering and chattering completely cover the voice you are trying to hear, you cannot get all the information you need just by focusing more closely on the person's lips. For many people, this difficulty is not a temporary one that ends when the background noise fades or the light is switched on. Some people's brains are missing information not because it is too dark or too noisy, but because a sense is not working properly. Ingenious devices, like glasses and hearing aids, have been invented to solve this problem, but sometimes they are unable to mend the broken sense. How, then, do we give the brain the information it needs? We already know that the brain uses other senses to collect missing information. Perhaps we can send the missing information through another sense.

LISTENING WITH YOUR WRISTS

Many people who have damaged hearing struggle to work out where sounds are coming from. This can cause a lot of problems. For example, it is hard to get out of the way of a truck that you suddenly hear hurtling toward you if you do not know where it is coming from! It is also hard for your brain to separate sounds that are coming from different directions, like the voice of the person in front of you and the music blaring from the speaker to your left.

Together with a team of researchers, I am currently investigating whether vibration on the wrists can be used to help people work out where sounds are coming from. When the ears are working well, your brain can pinpoint where a sound is by comparing how loud it is at each ear. As shown in Figure 1, if a sound is to your right, the soundwave travels through the air directly into your right ear. But to reach your left ear, the soundwave needs to first get past your head. Sound gets quieter when it is blocked by your head, just as sound gets

Figure 1

A person hears an explosion to their right. They have devices behind each ear that receive the sound. The sound from each ear is converted to vibrations that are delivered by wristbands on each wrist.

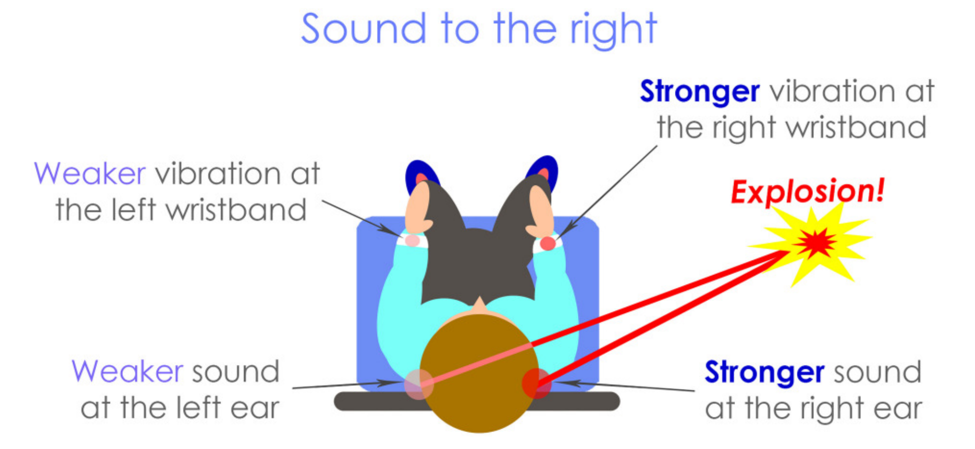

Figure 1

quieter when you block it by closing a door. This means that your brain can use a simple rule to work out where a sound is: if it is louder in your left ear then it must be to your left, and if it is louder in your right ear then it must be to your right. This is one of the main ways your brain works out where a sound is, and it is this rule that we took advantage of.

We converted sound into vibration, which we delivered using wristbands that silently buzzed against the skin. Sounds heard by the left ear were converted into vibration on the left wrist, and sounds heard by the right ear were converted into vibration on the right wrist. This meant that—just like for the ears—if a sound was to the right, the vibration was stronger on the right wrist, and if a sound was to the left, the vibration was stronger on the left wrist. We hoped that, by using the same rule that it uses for hearing, the brain would be able to work out where sounds are.

OUR EXPERIMENT

Our volunteers all had difficulties hearing and used cochlear implants, which are a type of surgically fitted hearing aid. They sat in a chair with speakers in a semicircle around them and with vibrating wristbands on each wrist (Figure 2A). We tested how well the volunteers could work out where sounds were coming from when using either only their ears, only the wristbands, or their ears together with the wristbands [1]. We played a sound from a speaker, then asked the volunteer which speaker the sound came from. We calculated how well they located the sound by measuring how far their answer was from the correct speaker. We measured this distance in degrees, as the angle between the correct speaker and the one they chose. We repeated this process over and over and calculated an average of all the scores. We were very pleased with what we found!

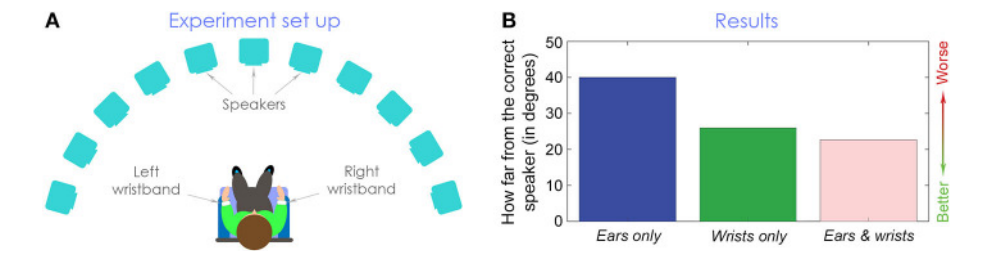

Figure 2

Figure 2

(A) In our experiment, a volunteer sits in a chair with vibrating wristbands on each wrist and with speakers in a semicircle around them. A sound is played from one of the speakers and the volunteer's task is to say which speaker that sound came from. **(B)** The bars show how far on average the correct speaker was from the one the volunteers said (in degrees). You can see that the blue bar (ears only) is much higher than the green or pink bars (wrists only or ears and wrists together). This means that the wristbands helped volunteers locate sounds more accurately. The pink bar is the lowest, which tells us that volunteers performed best when they used the wristbands and their ears together.

DID IT WORK?

Figure 2B shows the results. When using only their ears, the sound locations that our volunteers identified tended to be a long way from the correct sound location. However, when they used either the vibrating wristbands alone or their ears together with the wristbands, they tended to be much closer to the correct location. Interestingly, our volunteers performed best when they used the wristbands and their ears together. This is good news, as it suggests that the brain is happy to combine information from vibration on the wrists with information from sound at the ears.

The finding that the wristbands can hugely improve people's ability to locate sounds is especially exciting because these improvements were made after hardly any practice. We have since shown that, when people train for half an hour per day over 10 days, they keep on getting better at locating sounds [2]. Who knows how good they might get if they use the wristbands every day for months or even years?

A NEW KIND OF HEARING AID?

Besides helping people with hearing problems locate sounds better, we have been trying to improve other aspects of their hearing by sending missing sound-information through vibration on the wrists. For example, we have recently shown that vibration can help people with cochlear implants understand speech better when there is a lot of background noise [3, 4]. This is a common problem in places like busy classrooms, factories, and offices.

So far, we have only shown that this approach can help people when they are tested in the lab. Now, we are looking to create a device that can help people in their daily lives. We are building a new wristband (Figure 3), similar to a Smartwatch or a Fitbit, that people can wear outside the lab, as they go about their day [6]. We are working with one of the world's biggest producers of hearing aids and cochlear implants so that our wristband can connect wirelessly to their hearing devices to collect the sound at each ear. We are also developing our own small devices that collect sound at the ears for those people who do not already wear hearing devices.

Figure 3

Figure 3

The design for our new vibrating wristband. The lumps around the wristband have little vibrating motors inside them that buzz against the skin [Image credit: [5]].

If our wristbands work outside of the lab, they could help people across the world. They might be especially useful in poorer countries, where hearing loss is left untreated for many millions of people. In India, for example—a country of well over a billion people—less than a third of children with hearing problems go to school [7]. Adults with hearing problems in poorer countries are also much less likely to get jobs and so are often forced to live in poverty. Devices like cochlear implants are too expensive for most people, and poor countries lack the doctors and hospital equipment needed to fit them. The wristbands we are developing could overcome these problems. They can be produced very cheaply and can be fitted without the need for highly qualified doctors or expensive medical equipment. They could dramatically improve the job opportunities, education, and social lives of many millions of people with hearing problems. We are working as hard as we possibly can to make this happen.

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YOUNG REVIEWERS

ELLA, AGE: 11

Hello, I am Ella and I like food, nature, art, science and reading. I am funny, curious, kind and cycle every day to my secondary school.

LOTTE, AGE: 13

Hi, I am Lotte and I go to secondary school. I like reading and science. I have a pet leopard gecko called Gem.

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Mark is a senior research fellow who is jointly affiliated with the University of Southampton Auditory Implant Service and the Institute of Sound and Vibration research. He earned his M.Sc., in neuroscience at the University of Nottingham and specialized in hearing for his Ph.D., at the Institute of Hearing Research. He now leads the Electro-haptics Research Project (www.electrohaptics.co.uk), which seeks to aid people with hearing impairment by providing sound information through vibration. *M.D.Fletcher@soton.ac.uk

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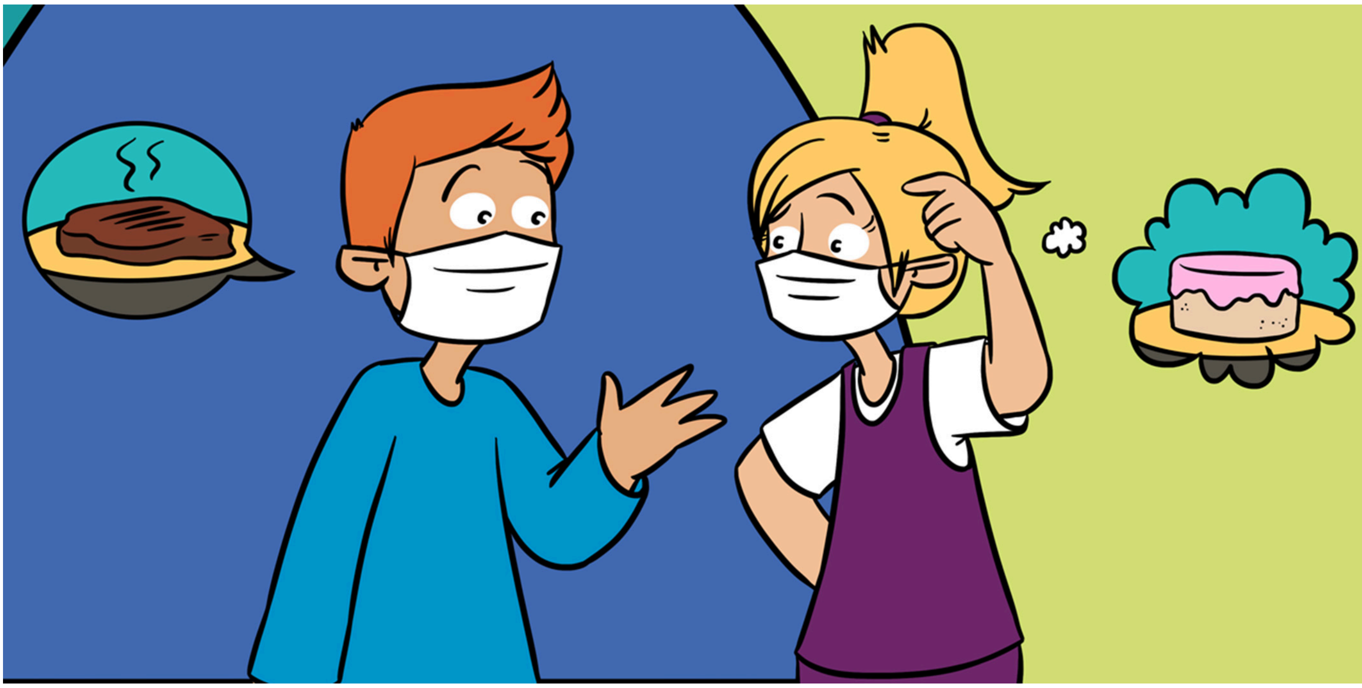

HOW WHAT YOU SEE CAN INFLUENCE WHAT YOU HEAR

Paula C. Stacey [*] ***and Christian J. Sumner***

NTU Psychology, Nottingham Trent University, Nottingham, United Kingdom

YOUNG REVIEWERS:

NOVA
AGE: 10

RONI
AGE: 13

We automatically use more than one of our senses to understand the world around us. When having a conversation, most of us use our ears to listen to what other people are saying. But you might be surprised to know that what you *see* is also very important in helping you to understand others. This article looks at how hearing and sight are combined and explains how both of these senses help us to understand speech. We demonstrate how important it is to see the faces of people who are talking, particularly when we are in noisy places. This topic has important implications for the wearing of face masks! It is really important that we think about how face masks may affect the ability of people to communicate with each other.

INTRODUCTION

Do you ever struggle to understand what your friends or teachers are saying when they are wearing face masks? Why is this? Nearly everyone benefits from seeing people's faces while they are talking. The various sounds people make when they talk require them to move their mouths in unique ways, and even though you might not be aware of it, your brain understands those specific mouth shapes! The shapes make it easier for us to understand people when we can see them talking.

The brain has specialized areas that process information from the senses and allow us to understand the world. Some of these brain areas automatically combine information across multiple senses. When information from one sense (hearing, for example) is unreliable, then we automatically rely more on information from another sense (like vision). This is why you will particularly notice the benefits of seeing people speak when you are in a noisy place.

In this article, we will begin by introducing you to the difference between sensation and perception, and we will use a well-known visual illusion to demonstrate how perception can sometimes be inaccurate. This will help you to understand that what you perceive does not necessarily correspond to the information that is in the world. We will then explain how our brains combine information across different senses, particularly sight and hearing.

MAKING SENSE OF THE WORLD

SENSATION

The process where our senses pick up information in the world.

PERCEPTION

The process where our brains make sense of information provided by the senses.

Your ears pick up sound waves and you hear them as sound. Your eyes pick up light energy, which gives you sight. We call these processes **sensation**. What your brain then does with the information from your senses is called **perception**. Most of the time, we assume that what we sense and what we perceive are the same thing. But sometimes our brains come to the wrong conclusions about what is out there! Perception can be a tricky job: it involves combining what our senses are telling us with what we already know about the world, to make the best possible guess about what is happening. We can misunderstand, or misinterpret, sensations, and then perceive something that just is not true.

Visual illusions can be fascinating to look at, and they give us a really good example of how sometimes the brain can misinterpret sensations to give us the wrong perception. Have a look at Figure 1. Which car do you think is the biggest? Now take out a ruler and measure them. Were you right?

At a first glance, you might think the top car is larger than the bottom one, but they are actually the same size! We call this a visual illusion because the picture fools your brain into thinking the cars are different sizes. This works because clues in the picture (the shape of the road, in this example) make the top car appear to be further away than the bottom car. Normally, things that are far away look smaller than things close to us (next time you are on a car journey look at the size of the cars in the distance compared to those close by), so the car at the top

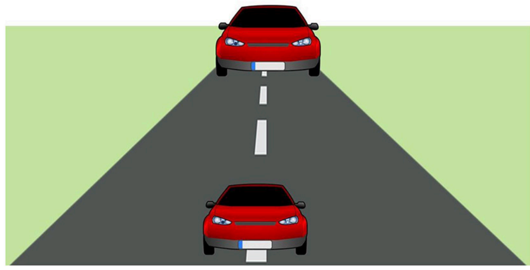

Figure 1

Figure 1

Visual illusion. These cars are the same size, yet the top car is usually perceived to be larger. This is because the cues in the picture tell us the top car is further away, so the brain automatically "scales up" the image. This example shows us that what our senses observe and what our brains perceive are not always the same.

of the road *should* appear smaller because it is further away. The brain somehow knows this, so it "scales up" the perception of the car's size automatically. In real life, this mental adjustment usually works well and helps our perception of the world to make sense.

COMBINING OUR SENSES

We know that our brains often use both vision and hearing to understand the world. This can make it easier for our brains to correctly determine what is going on than if we only used one sense. But the same way a visual illusion can play tricks on the brain *via* the eyes, an audio-visual illusion can confuse perception if the information coming from hearing and vision do not match. This was illustrated by an experiment performed by Harry McGurk and John McDonald in 1976 [1]. These scientists recorded a person saying the sound "ba." They then made a silent video of the same person saying the sound "ga." They played the sound recording ("ba") alongside the video ("ga") and asked volunteers to say what sound they heard. You might be surprised to learn that most volunteers said they heard the sound "da"! This is because their brains mashed up what they saw and heard and made a guess at what the sound really was. The amazing thing about this experiment is that it really does change the way the words sound, which is called the **McGurk effect** (Figure 2). The experiment showed that seeing a talking face can have a powerful effect on the sounds people perceive[1]. The effect is also found with other combinations of sounds. The perception of speech is really the result of the brain making the best guess it can from what we see, what we hear, and what we already know about language.

MCGURK EFFECT

An audio-visual illusion that occurs when hearing one sound (e.g., "ba") while also seeing the mouth movements that accompany another sound (e.g., "ga") results perception of new sound (e.g., "da").

[1] Have a look at this video for a demonstration of the effect: `https://www.youtube.com/watch?v=jtsfidRq2tw&t=20s`.

HOW SIGHT HELPS US HEAR IN NOISY PLACES

In the real world, lip movements usually match the sounds coming from people's mouths, so seeing someone talk usually helps us to perceive the right word. This visual information tends to be more helpful for understanding speech when the conversation takes place in a noisy setting. Try sitting in a quiet room with a friend. You will probably find it quite easy to understand what your friend is saying.

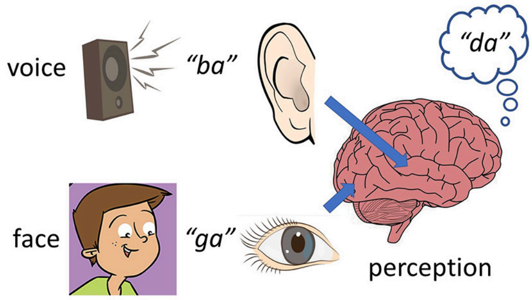

Figure 2

Figure 2

The McGurk effect. In this illusion, hearing one sound (e.g., "ba") while also seeing the mouth movements that normally accompany another sound (e.g., "ga"), often results in listeners perceiving a new sound (e.g., "da"). This tells us that the brain automatically combines information across the senses, to help us understand the world.

Now turn the television on with the volume up loud. How easy is it to understand your friend now? It is much harder to hear and understand what someone is saying if the background is very noisy. If you look at your friend's face and lips, you are more likely to correctly guess what is being said.

MEASURING HOW VISION AFFECTS UNDERSTANDING OF SPEECH

We carried out some experiments on how background noise affects understanding of a sentence [2]. First, we videoed and recorded a volunteer saying several different sentences (such as "A large size in shoes is hard to sell."). Then we played these recordings to other volunteers and asked them to repeat what they heard, and we counted how many words they got right. We repeated this experiment with lots of volunteers, adding various levels of background noise, or reducing the volume of the speech signal. The relationship between the speech signal and the background noise is called the **signal-to-noise ratio**. Sometimes we only played the sound of the person speaking, and other times we also showed the video of the person, so volunteers could both see and hear the speaking person.

SIGNAL-TO-NOISE RATIO

A measure of the strength of the "signal" (in our case, speech) against the background noise.

We plotted the information we gathered on a graph (Figure 3). When the background noise was much louder than the person speaking, our volunteers could not identify any words correctly. But when the sentences were louder than the background noise, our volunteers heard most of the words correctly. Between these two situations, volunteers could identify some, but not all of the words correctly. Our results clearly show that people can understand speech with more background noise present if they can see the faces of talkers. This effect explains your experience of seeming to hear better when you can see people speaking, especially when you are in a noisy place. Previous studies have found similar results [3].

Why is this important? Imagine you are working in a noisy factory with loud, dangerous machinery. Now imagine your co-worker is trying to explain exactly how to use a machine. With all that noise in the

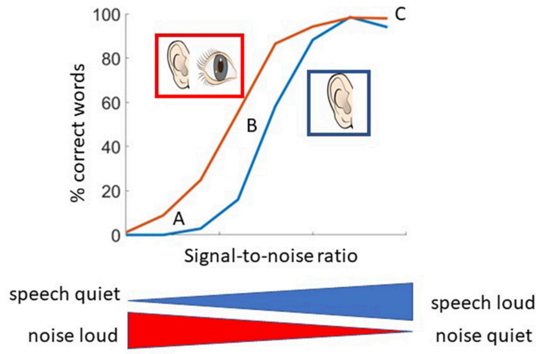

Figure 3

Figure 3

When the background noise was much louder than the person speaking (low signal-to-noise ratio), volunteers could not identify any words correctly **(A)**. But when sentences were louder than background noise, volunteers heard most of the words correctly **(C)**. In between, volunteers could identify some, but not all, words correctly **(B)**. When volunteers could both see and hear the person talking (red line), they got more words correct than when they could only hear the talker (blue line). So, it is easier to understand speech when we can both see *and* hear the speaker.

background, do you think you would be able to hear the instructions clearly? What if your co-worker was wearing a safety mask while talking? In this sort of environment, making a mistake could be very dangerous and might even result in injury.

BENEFITS OF VISUAL INFORMATION FOR PEOPLE WITH HEARING LOSS

Have you ever tried to understand what someone is saying by *just* looking at their face, without hearing their words? You may find you are better at this task if you have poorer hearing. People who are deaf or hearing impaired are generally better at **lip reading** than people with normal hearing [4]. This skill probably developed over time as these people lost their hearing and had to pay closer attention to their other senses.

LIP READING

Understanding speech from mouth movements alone.

During the coronavirus outbreak, wearing face masks was often a requirement. Masks make lip reading very difficult for people who need to do so. In the UK, campaigners helped persuade the government to provide see-through face masks to help deaf people to communicate. In our research, we try to understand how lip reading helps communication, and especially how it helps people with hearing problems.

CONCLUSION

Visual information is really important to help us understand the sounds we hear. What we see is especially important for understanding speech when the sound we are listening to is affected by either background noise or poor hearing. There is still a lot we do not understand about how the brain combines what we see and what we hear. Next time you are in a noisy environment, think about how much you rely on seeing the faces of the people who are speaking, and about what could be done to make visual speech information more accessible for people who have trouble hearing.

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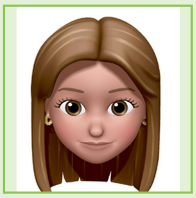
YOUNG REVIEWERS

NOVA, AGE: 10

My name is Nova and I am in 5th grade. My favorite subjects are writing, science, social studies and reading. When I grow up, I would like to be an architect, because I like art and I also like building. I think it is important for kids to be curious so they can learn. Albert Einstein said that he did not have a special brain, but he wondered how the universe worked, so he went out and learned, so he could figure it out.



RONI, AGE: 13

Roni was born in Jerusalem but lived most of her life in Tel Aviv. She is a 7th grade student in Pelech High School, Tel Aviv. She lived in the US for three years as a baby and toddler until moving back to Jerusalem and then to Tel Aviv. She studied elementary school in the Meshutaf school, Tel Aviv, except 5th grade which she spent in Berkeley CA. Roni is interested in science but also loves gymnastics and singing.

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Paula C. Stacey is a principal lecturer in psychology at the Nottingham Trent University. Paula completed her Ph.D. on the topic of auditory training for adults who use hearing-assistance devices called cochlear implants. She is currently interested in how people use visual information to help them to understand speech in noise. *paula.stacey@ntu.ac.uk

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Christian J. Sumner is an associate professor in auditory neuroscience at the Nottingham Trent University. He has a background in computer science, and so views the brain as a big computer—and wants to understand the program for how we hear! He has wide interests in the field of hearing, from how the brain separates out simultaneous sounds (like instruments in an orchestra), to how single neurons in the brain process sound, to how hearing changes as we age.

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SPEECH PROSODY: THE MUSICAL, MAGICAL QUALITY OF SPEECH

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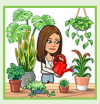
YOUNG REVIEWERS:


ANNA
AGE: 12


TORBEN
AGE: 13

When we speak, we can vary how we use our voices. Our speech can be high or low (pitch), loud or soft (loudness), and fast or slow (duration). This variation in pitch, loudness, and duration is called speech prosody. It is a bit like making music. Varying our voices when we speak can express sarcasm or emotion and can even change the meaning of what we are saying. So, speech prosody is a crucial part of spoken language. But how do speakers produce prosody? How do listeners hear and understand these variations? Is it possible to hear and interpret prosody in other languages? And what about people whose hearing is not so good? Can they hear and understand prosodic patterns at all? Let's find out!

During their first year at Hogwarts, Harry Potter and his friends learn the levitation charm "Wingardium Leviosa". While practicing, Harry's best friend, Ron, has a hard time making the feather on his desk obey his command and lift into the air. Hermione knows exactly why: "You're saying it wrong. It's Levi-*o*-sa, not Levio-*sa*". "You do it, then, if you're so clever. Go on, go on!", replies Ron. With a swish and a flick of her wand, Hermione speaks the charm "Win-*gar*-dium Levi-*o*-sa!" and her feather slowly rises from her desk. It turns out that the levitation charm only works if you say the magic words properly. In other words, *what* you say matters, but *how* you say it also makes a big difference. Hermione actually uses **speech prosody** to convince her feather to levitate.

SPEECH PROSODY

The musical quality of speech, like stress, rhythm, and intonation. It can express sarcasm and emotions, and it can also change the meaning of speech.

WHAT IS SPEECH PROSODY?

Speech prosody is often described as the musical quality of speech [1]. If you think of vowels and consonants as the sounds of language that make up *what* you say, then prosody is related to *how* you say these sounds. When Hermione corrects Ron's pronunciation, she does not correct any vowels or consonants. In fact, the vowels and consonants in "Levi-*o*-sa" and "Levio-*sa*" are the same. What Hermione corrects instead is the **stress pattern**. Ron mistakenly places emphasis on "*sa*" in "Leviosa" when he is supposed to place it on "*o*". Without the correct stress pattern, the words "Wingardium Leviosa" no longer have the intended meaning and the levitation charm does not work. Now, you might think: "great example, but the Harry Potter stories are fictional, and I could never make an object fly". This may be true, but speech prosody works just as well in our Muggle (non-magic) world. Have you ever thought about how "object" can be pronounced in two ways? When we mentioned "object" a few sentences ago, we meant the noun that refers to a thing that can be seen and touched. In this context, you would pronounce "object" with stress on the first part of the word, like "*ob*-ject". But if you were to stress the second part, instead, it takes on a new meaning. The verb "ob-*ject*" describes someone expressing disagreement. Think of how Hermione ob-*jects* to Ron's pronunciation of the levitation charm. So, by simply changing the stress pattern, the word changes from a noun to a verb. Now that really *is* magic!

STRESS PATTERN

The way parts of a word or sentence are stressed or unstressed. Stressed parts are emphasized by increasing the relative pitch, loudness, and duration.

Speech prosody is more than just changing stress patterns though. When you speak, everything you do with your voice that is not directly related to pronouncing vowels and consonants is prosodic. Think of the **rhythm** and **intonation** of speech. Prosody makes speech sound less monotonous and boring. It can also change the meaning of speech—the meaning of a whole sentence can change by emphasizing different words! You can also make serious sentences sound sarcastic, or make happy stories sound sad, when you change the tone of your voice. Or you can turn statements into questions by changing the prosodic pattern. Try saying this sentence aloud: "See

RHYTHM

The structured organization of speech parts over time, like the beat of a song. Speech usually has a rhythm that you can tap along to.

INTONATION

The way pitch varies over time, like the melody of a song.

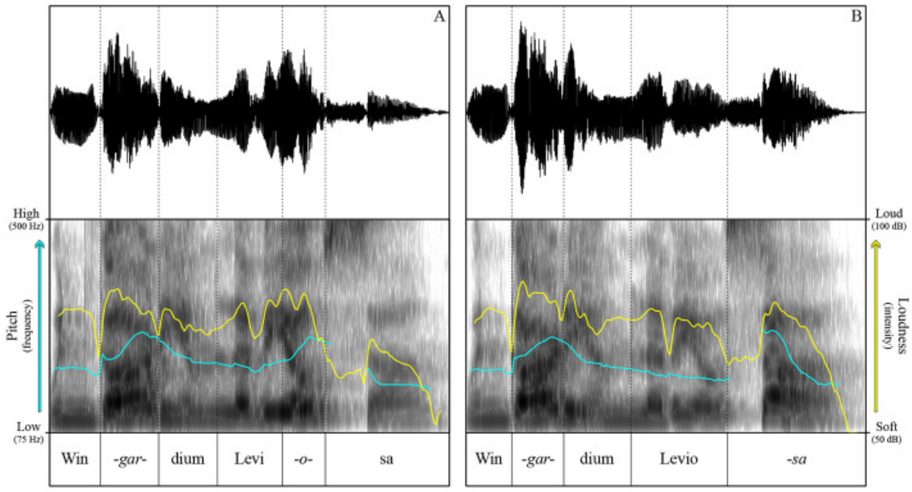


Figure 1

Figure 1

The different pronunciations of "Wingardium Leviosa" visualized in two ways. The speech waveform (top) shows the loudness of the recorded speech over time and the spectrogram (bottom) shows the loudness at different frequencies over time. In the spectrogram, the blue lines show the voice frequency, related to the perceived pitch, and the yellow lines show the intensity, related to the perceived loudness. You can see in **(A)** that "*o*" is higher (blue) and louder (yellow) than the other parts of "Levi-*o*-sa" and in **(B)** that "*sa*" is higher (blue) and louder (yellow) than the other parts of "Levio-*sa*".

you tomorrow!". Now say the sentence again, but this time turn it into a question: "See you tomorrow?" Notice how your voice goes up in pitch at the end of the sentence? This is speech prosody!

HOW DO WE USE AND UNDERSTAND PROSODY?

When we speak, we can (and do!) vary how high or low, how loud or soft, and how fast or slow our speech is. This variation in **pitch**, **loudness**, and **duration** is what creates the prosodic patterns of speech [1]. Everyone uses prosody when they speak. Even Ron uses prosody when he says "Levio-*sa*" by pronouncing "*sa*" slightly higher, louder, and longer than the other parts of the word. Compare this to when Hermione says "Levi-*o*-sa". She pronounces "*o*" higher, louder, and longer than the other parts of the word (Figure 1). Whatever the prosodic pattern may be, it is always described in terms of the *relative* increase or decrease in pitch, loudness, and duration.

PITCH

How high or low speech is. What we hear as pitch can be measured as the frequency of a voice—when the frequency goes up, the perceived pitch goes up.

LOUDNESS

How loud or soft speech is. What we hear as loudness can be measured as the intensity of a voice—when the intensity goes up, the perceived loudness goes up.

DURATION

How long or short speech is. The duration of speech is measured over time.

When we listen to speech, we can usually hear the variation in pitch, loudness, and duration that a speaker produces. These prosodic patterns help us understand what was said [2]. Over time, we learn to recognize commonly used prosodic patterns and attach meaning to them. For example, when you were very young, you learned that someone is asking a question if their voice rises in pitch at the end of the sentence. But you may not always be aware of such connections. As a Muggle, you might never have realized how important the correct stress pattern is in "Levi-*o*-sa", since these magic words have no function in the Muggle world. Ron, on the other hand, *must* learn the correct stress pattern if he wants to make objects fly. As a wizard, he has to make the connection between the stress pattern "Levi-*o*-sa" and its function: producing a proper levitation charm.

HOW DOES OUR NATIVE LANGUAGE INFLUENCE PROSODY?

When Harry, Ron, and Hermione are in their fourth year, students from Durmstrang and Beauxbatons visit Hogwarts to compete in the Triwizard Tournament. These international students speak English, but English is not their *native* language. Now, imagine that Hermione wants to teach one of these international students the levitation charm. You might think that the difference between "Levi-*o*-sa" and "Levio-*sa*" would be obvious to everyone, but in fact, people who speak another language might not be able to tell the difference as easily as you or Ron can. This is because not all languages use the same prosodic patterns. Have you, for instance, ever noticed how English or German sound very different from French or Italian? We have seen that, in English, a word can change meaning if you change the stress pattern (like in "*ob*-ject" and "ob-*ject*"), but in some other languages, stress patterns are always fixed. In French, for instance, stress is always on the final part of a word. So, Fleur, a student from the French wizarding school Beauxbatons, will probably say "Levio-*sa*", just like Ron does. But the question is: would Fleur realize that the correct pronunciation has a different stress pattern? Listeners tend to stick to what they know, and their native languages may influence how they perceive speech in another language. If Fleur listens to Hermione teaching her the spell, she might be able to hear that "Levi-*o*-sa" is different from "Levio-*sa*", but she will probably not realize how important the stress contrast is for the meaning of the word because stress contrasts do not exist in French. So, she may not *recognize* the stress contrast for what it is [3]. But do not worry, she can still learn to recognize it and if anyone can teach her, it is Hermione!

HOW DOES OUR HEARING ABILITY INFLUENCE PROSODY PERCEPTION?

Good hearing is important for understanding prosody. After all, it would be hard to link prosodic patterns to their function if you could not hear the patterns in the first place. This is the case for listeners who hear very little or are completely deaf. Fortunately, a device called a **cochlear implant** (Figure 2) can bring back some hearing for these listeners. A surgeon implants a wire with tiny electrodes into part of the inner ear called the cochlea. This is the place where healthy ears transform soundwaves into electrical signals that are then sent to the brain via the auditory nerve. For listeners with cochlear implants, the transformation of soundwaves into electrical signals happens via the device and the electrodes send these signals to the auditory nerve directly. Listening with a cochlear implant is sometimes called electric hearing. In a sense, it is magical that this device can bring back some hearing, but electric hearing is far from perfect. Listeners with cochlear implants have difficulty hearing pitch differences [4]. If Ron had a

COCHLEAR IMPLANT

An electronic device that can bring back hearing for deaf individuals. It uses electrodes to send sound-like electrical signals to the auditory nerve directly.

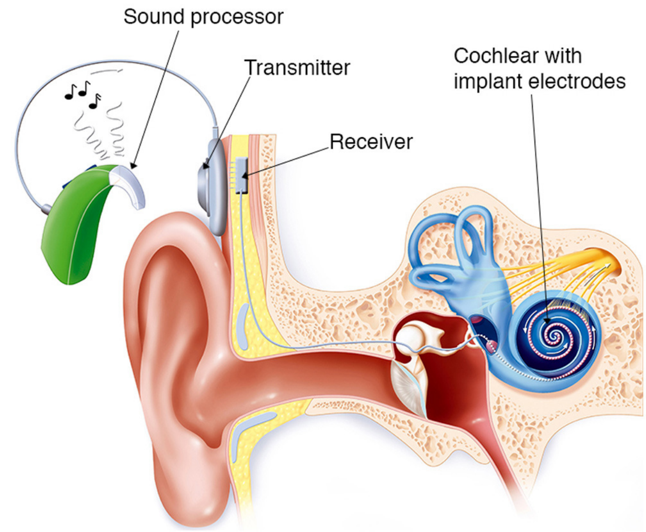


Figure 2

Figure 2

Ear with a cochlear implant. The wire with electrodes is implanted in the spiral-shaped cochlea, which is the blue part that looks like a snail. The electrodes of the cochlear implant send sound-like electrical signals directly to the auditory nerve. The yellow lines attached to the cochlea are part of the auditory nerve. The auditory nerve carries the electrical signals to the brain (Image credit: https://media.healthdirect.org.au/images/inline/original/cochlear-implant-illustration-445004.jpg).

cochlear implant, it would have been very hard for him to hear that Hermione pronounces "*o*" slightly higher in pitch than the other parts of the word "Levi-*o*-sa". However, he would still be able to hear it as louder and longer, so there is a chance he would be able to learn the correct stress pattern with practice. In time, he would probably still be able to make sense of the prosodic pattern based on what he *could* hear, although this would be much harder work than if his hearing was not impaired.

WHAT IS THE MAGIC OF SPEECH PROSODY?

The fact that speech prosody can make objects fly is pretty magical. But do you know what is even more magical? That you now know how important speech prosody is! It is like you have been waiting for a Hogwarts letter announcing you are off to Wizarding school so you can finally learn all about the magical powers of speech prosody. Well, here it is. Your letter has arrived. So, what are you waiting for? Get ready to go out into the Muggle world and use your speech prosody magic!

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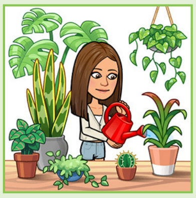
YOUNG REVIEWERS



ANNA, AGE: 12

Hi, my name is Anna. I am 12 years old and I am going to start the 8th grade. My favorite subjects are science, English literature, and art. My hobbies are reading, watching TV, writing letters to friends and family, and cooking. When I grow up I want to be an engineer and later work in fashion and get a degree in neuroscience. I am a productive person but I need to be interested in the thing I do or else I do not put a lot of effort.

TORBEN, AGE: 13

Torben is motivated, talented, and intelligent. In school, he likes science, math, history, and geography. He loves to read books and is learning Spanish, French, and German. He plays piano and sings in several choirs and has won several local and national music awards. He has a special interest in neuroscience-related topics. His English teacher selected him to report on the COVID-19 crisis. To do so, he wrote a Spotify segment and interviewed his teachers about how the pandemic impacted teaching and learning. He enjoys biking, soccer, hiking, swimming, horseback riding, and other activities that he carries out with his boyscout troop.

AUTHORS

MARITA K. EVERHARDT

I am a Ph.D. student at the University of Groningen/University Medical Center Groningen and I love studying sounds. I am fascinated by what we can do with our voices and by how we can make sense of what we hear. In my Ph.D. project, I investigate how adolescents perceive speech prosody in a non-native language with simulated electric hearing. In my free time, I also like to surround myself with sounds: I love music and go to concerts/festivals a lot. I also enjoy playing card/board games, reading books (including Harry Potter!), baking cookies/cakes, doing yoga, and traveling. * m.k.everhardt@rug.nl

ANASTASIOS SARAMPALIS

I am very happy: I get to spend most of my time figuring out how the world works and helping others do the same thing. In other words, I work at the University of Groningen, in the very North of The Netherlands, where I try to understand how the human auditory system works and teach many brilliant young people how to get to grips with knowledge. What I am mostly curious about is how people understand speech, especially in situations that are not perfect, and how mechanisms in the brain and the hearing system work together.

MATT COLER

I am an associate professor and director of the master's program in voice technology at the University of Groningen Campus Fryslân. My research began with fieldwork on indigenous languages spoken in remote Peru. These days, I work on voice synthesis, speech recognition, and acoustic perception, recognition, and sensation! I am interested not only in language and music, but in the intersection between the two. I am very curious about the relationships between signal and meaning: What part of an auditory signal is a cue to meaning? How can we explain how the "same" signal can have different meanings? What are the differences between hearing and listening?

DENIZ BAŞKENT

I am a professor at the University Medical Center Groningen, a hospital, yet I am an engineer. With this combination, I love studying all aspects of hearing ears, hearing brains, hearing problems, and hearing devices. Working in a multidisciplinary team where everyone has a different background, I love challenging my team members and being challenged by them—which is just what happened when we were writing this paper. Only such discussions will lead to great scientific knowledge and products—which is also just what happened with this paper.

WANDER LOWIE

I am a professor at the University of Groningen, and I am fascinated by how people learn another language on top of a language they already know. Some of the questions we try to answer in our research include: how does our first language influence second language learning, why are some people better at learning additional languages than others, and what are the best conditions for language learning to take place? Studying how people manage to learn a second language under difficult circumstances, like when people have hearing problems, helps us to understand the process of language learning.

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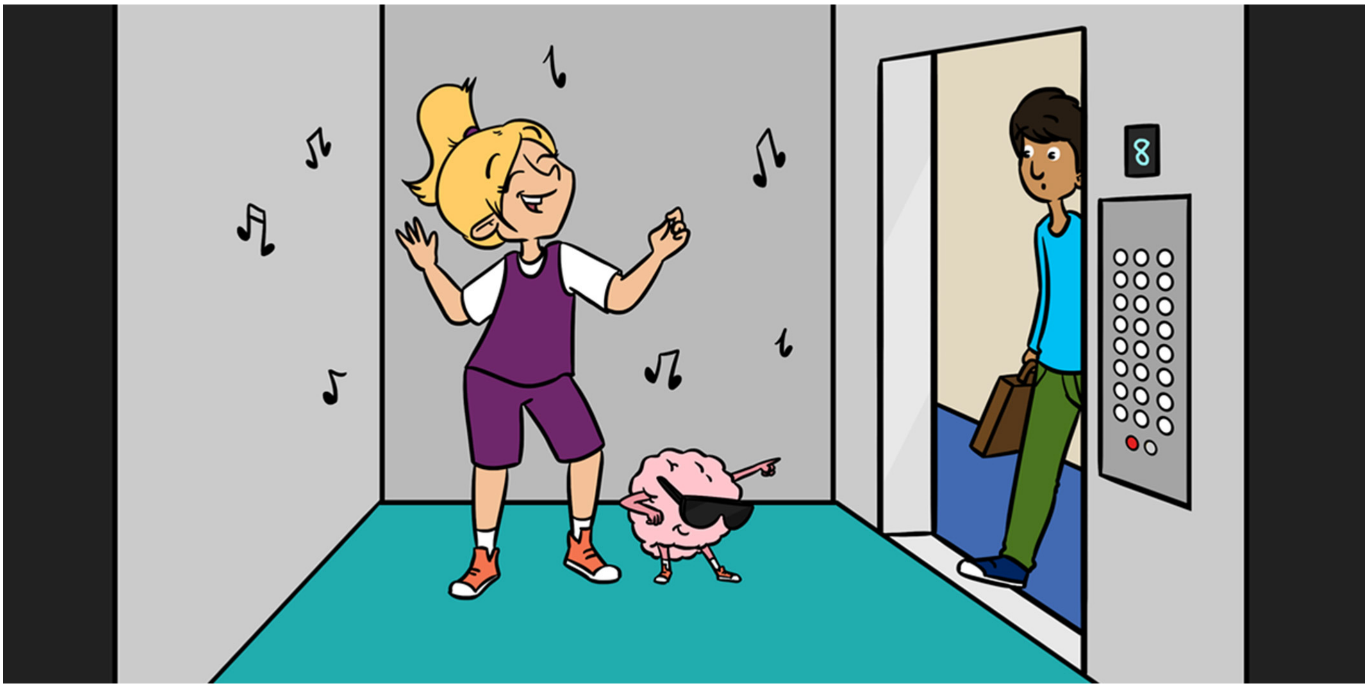

WHY DO HUMANS—AND SOME ANIMALS—LOVE TO DANCE?

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YOUNG REVIEWER:

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Have you ever lost yourself in dance? Or have you bounced your foot or wiggled with the rhythm of music? Do you find yourself smiling when you do so? You are not alone! From a simple drumbeat to popular rock-and-roll, the sound of music makes people of all ages move along in time to the beat. We see people tapping, clapping, and bouncing when listening to their favorite songs at a concert hall or on their phones. The urge to move with music has been part of all cultures across the world for as long as we have been studying humans. There are even some animal species that like to dance! Why is this? In this article, we explain what it is about music that makes us want to move—and what is happening in our brains when we do. Let us dive into the science behind dance.

Dance means the act of moving one's body rhythmically to music. Music is simply a mixture of sound waves made by a human voice or a musical instrument. Sound waves are invisible and travel through the air and into our ears. When the sounds reach our ears, they send signals to a part of the brain called the **auditory cortex**. The signals then travel to other areas of the brain. Through this process, music "lights up" the brain regions that are responsible for thinking and understanding—and for reward, emotion, language, and movement. Let us find out more about how music affects our minds and bodies!

AUDITORY CORTEX

A brain region that processes auditory information in humans and some animals.

RHYTHM

A broad term in music referring to the certain pattern of sound (note) and silence (rest).

METER (METRE)

In music, it refers to the regularly recurring patterns of stressed and unstressed beats.

RHYTHMIC ENTRAINMENT

A temporal coupling of two independent oscillators, by which one oscillator's frequency entrains the frequency of the other.

VIDEO 1

Rhythmic entrainment of five metronomes on a common base.

OSCILLATOR

An object moving back and forth with a set regular rhythm.

OUR BODIES GET SYNCED TO THE RHYTHM OF MUSIC

When you think about music, you might imagine your favorite song or band. Or you might think about the classical or jazz music you are learning to play on an instrument. A scientist would describe music as a series of sounds and silences that happen in a particular pattern over a certain time period. The pattern of musical sound is called **rhythm**. Most music also has regular beats, called **meter**, which is what makes us want to move our bodies in time with it. It is easy to move to music with a meter because we can guess what is coming next. Our internal body rhythms start to match up with the rhythm or meter of the music. This process is called **rhythmic entrainment**.

Video 1 demonstrates rhythmic entrainment. Have you ever seen an old-fashioned grandfather clock? Hanging beneath the clock face is a long bar with a weight on the end, called a pendulum. As the pendulum swings from side to side, its movements turn a series of cogs, which then turn the hands of the clock. Pendulum clocks were invented in 1666 by a Dutch physicist, Christian Huygens. Huygens placed two pendulums on the same wall and started swinging them at different times. Soon, the two pendulums started swinging back and forth in time with each other! They had become synchronized. This is a great example of entrainment. How does this happen?

An object moving with a set rhythm, like the pendulum of a clock, is called an **oscillator**. The word "oscillate" comes from the Latin word "oscillat" which means "to swing." When the pendulums start to oscillate, they transmit small amounts of energy to each other through the base they are standing on. When one pendulum swings, it creates energy that is transferred through the base to the second pendulum. When the second pendulum swings back, it also makes energy and passes it back to the first pendulum. It is a bit like two people having a conversation. As this small energy exchange repeats, it gradually changes how quickly each pendulum oscillates. The faster oscillator slows down, and the slower oscillator speeds up, until they move at the same speed. Once the oscillators are synchronized, they stop transmitting energy between them. Being synchronized uses the least amount of energy.

Many things in nature have their own rhythms. From the tiniest atoms to our own heartbeats or breathing, the world is full of things that oscillate. Rhythmic entrainment—synchronization—is happening all around us every day, including when we listen to music. The oscillator of the body becomes entrained to the rhythm of music. Our feet begin to tap or stamp, we bounce up and down, or we walk along in time to the music, the same way the pendulums started moving together in Huygens' experiment. Even our heartbeat and breathing can start to keep time with the music [1]!

OUR MINDS EMOTIONALLY BOND TO MUSIC

We now know why we move along in time to music. But why do we *enjoy* dancing so much? For centuries, psychologists (who study our thoughts and behaviors) have been interested in how music affects our emotions. Most forms of music express emotions through tempo, melody, and rhythm. Think about a cheerful song. Is it fast or slow? Is it upbeat or down? Now think about a sad song. Is it different from the happy song? A happy birthday song might make us feel good because the melody and rhythm are happy and bright and because we often hear or sing that song when having fun with family or friends. We associate the birthday song with good times, so when we hear it, we remember those times and feel happy as a result!

The way we move our bodies is deeply connected to our emotions and feelings. When we are happy, we might jump around or wave our arms in the air. When we are sad, we might hunch over or fold our arms around our bodies. But the opposite is also true. Hunching over and wrapping our arms around our bodies can *make* us feel sad. Jumping around and waving our arms can *make* us feel happy! Expressing our emotions through movement is called the **embodiment of emotions**.

EMBODIMENT OF EMOTIONS

The physical representation or expression of one's emotional states.

Music is a great example of the embodiment of emotions. This is because music performers express emotions through movements, which causes listeners to have similar emotions. So, listening to jolly music can make us feel happy and move our bodies in a jolly way by jumping, clapping, or singing along, which makes us feel even happier! Think about how a ballet dancer might move to a slow, sad tune. Or how a rock star might bounce to a happy, energetic song. In this way, we can use music and movement to show others how we feel. In essence, we move to music to express, experience, and enrich our feelings through melody or rhythm. Scientists have confirmed that music helps us feel and express our emotions. So, when we dance to upbeat music, we can not help feeling happy!

MUSIC LIGHTS UP THE BRAIN

The brain region that causes movement is called the **primary motor cortex**. When we hear music, this part of the brain is activated and encourages us to move. Another brain region is also at work when we listen to music—the **limbic system**, which is the part of the brain associated with reward and emotions. The limbic system triggers the release of body chemicals called hormones, which make us feel good. So, listening and moving to music can cause our bodies to release feel-good hormones. When moving our bodies in time to music, our feelings and emotions also bond with the music.

PRIMARY MOTOR CORTEX

A brain region that provides the most important signals to produce skilled movements.

LIMBIC SYSTEM

The collection of brain structures that are involved in emotion processing and behaviors.

Psychologists think that brain cells called **mirror neurons** also play a role in our enjoyment of music. Mirror neurons are brain cells that are activated when we see other people doing something [2]. For example, if your friend yawns, your eyes see them opening their mouth wide and your ears hear a yawning sound. This triggers mirror neurons in your brain that make you want to yawn, too! Try fake-yawning in front of a family member and see what happens!

MIRROR NEURONS

A set of neurons in the brain that modulate a specific action in humans and some animals or when they observe the same or similar action in others.

Mirror neurons also help you experience what is expressed by music performers. For example, when watching a band, your mirror neurons might encourage you to play air guitar while your favorite rock star is playing *real* guitar. Making similar movements to people performing music helps us relate to the emotions the musicians are expressing [1]. When several people move and feel the rhythm and emotions of music at the same time, their brains mirror each other's behaviors and they become socially bonded. See Figure 1 for an overview.

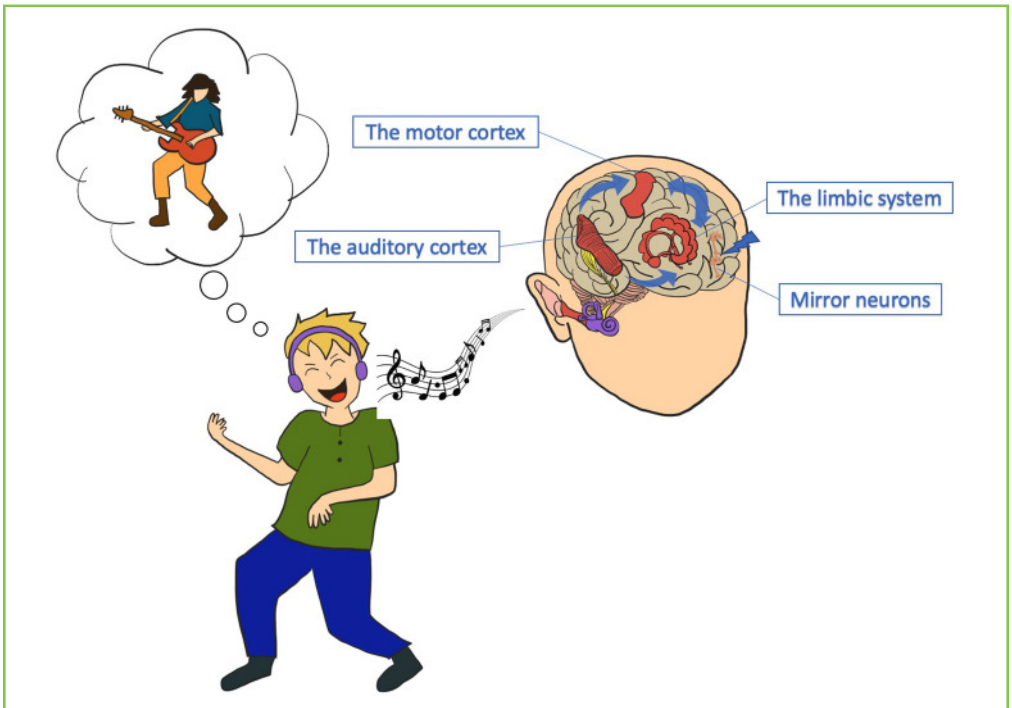

Figure 1

Figure 1

A person playing air guitar. The auditory cortex interprets the rock music and delivers the signals to the limbic system and the motor cortex, to create emotional and motor reactions. Mirror neurons play a crucial role in this process, helping to mimic the motion of guitar playing and reflect the feelings of the musician (Image credit: Jiyeong Hong).

WE ARE ALL BORN TO ENJOY DANCING

We now know why people enjoy listening and moving to music. Our dance moves might improve as we get older, but we are all *born with* the ability to dance. Scientists studied infants 5 months to 2 years old [3]. They played a variety of music, including classical pieces by Mozart and Saint-Saëns, children's songs, and drumbeats, as well as non-musical sounds like recordings of people talking. They found that babies moved more rhythmically when hearing music than when hearing non-musical sounds, and they smiled more when moving with music! These findings show that people are literally born to enjoy dancing, although everyone has their own unique desire and ability to dance. See Figure 2 for an overview.

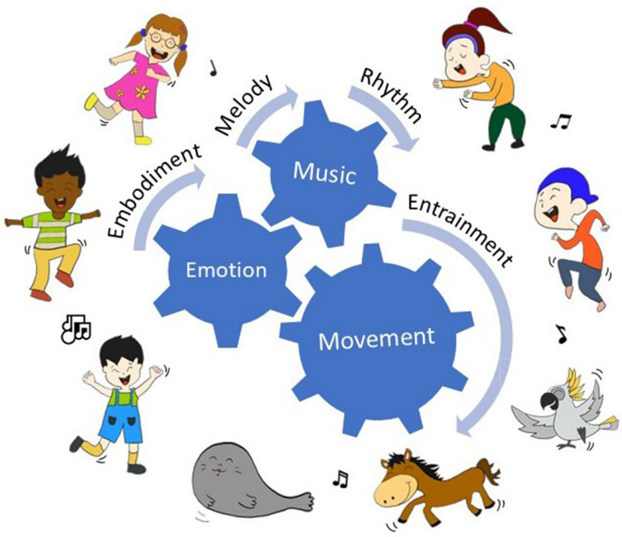

Figure 2

Figure 2

Dance often demonstrates our emotional and motor (movement) reactions to music. It is universal across most human societies and cultures. Entrainment and embodiment play a crucial role in dancing. Dancing has also been observed in some animals, although animals may not have sophisticated feelings like humans (Image credit: Jiyeong Hong).

SOME ANIMALS CAN DANCE, TOO!

Studies have shown that it is not just humans who dance. Some animals can entrain to music too. The most famous example is a parrot called Snowball (Video 2), whose movements consistently matched the rhythm of music in an experiment [4]. Some other examples of dancing animals include a sea lion (Video 3) that bobbed its head to a metronome and other rhythms, a bonobo that spontaneously drummed in synchrony with a scientist, and a horse that seemed to be trotting in time with music [5].

VIDEO 2

Snowball's tribute to Michael Jackson.

VIDEO 3

A scientific recording of a sea lion's beat keeping.

Scientists have suggested that animals may learn to move to the beat of music for food rewards or social bonding. The sea lion was trained for months with rewards of fish, and the parrot was rewarded with praise, which made it feel close to its human trainers. For us humans, engaging in music and dance helps us bond with others, contributing to the formation of unique cultures over thousands of years [5].

CONCLUSION

There is still a lot to discover about how humans and animals engage with music. Based on our current knowledge, we now understand that almost all humans and some animals can move to music. They choose to do so because it makes them feel good. Hopefully, in the future, you might join us to explore the science behind dance and music.

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YOUNG REVIEWER

AYA, AGE: 14
Aya is a 14 year old who loves biology, especially anything related to cells. She also loves books, sci-fi and R&b. Outside of school, she spends her time reading, playing volleyball and exploring molecular biology!

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K. SHIN PARK
Shin received his doctorate in health and human performance from the University of Florida. He is currently a postdoctoral researcher in the Physical Activity and Cognition Lab at the University of North Carolina at Greensboro. His research interests include discovering the mind-body mechanisms of music appreciation and developing music-based ways to promote physical activity and mental health. When Shin is not writing for or thinking of his research projects, he is most likely working out at his home gym or going on adventures with his awesome wife, Jiyeong (Joy) Hong, who used to be a music teacher and drew the figures in this paper! *k_park4@uncg.edu

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Madeleine is a neuroscientist with a focus on the development of rehabilitation programs for older adults with neurodegenerative diseases. She has a degree in dance performance from Tisch School of the Arts of New York University, and she had a successful ballet, ballroom, and contemporary dance career prior to returning to graduate school. Then, she completed her Ph.D., in Movement Science at Washington University and completed postdoctoral training in geriatric rehabilitation at the Atlanta Veteran's Administration Hospital and Emory University. She is currently an associate professor of medicine at the Emory University School of Medicine, Department of Medicine, and a research health scientist at the Atlanta Veteran's Administration Center for Visual and Neurocognitive Rehabilitation. She and her husband love moving to music with their two awesome children, Marcel and Mary Celeste.

CHRISTINA E. HUGENSCHMIDT
Christina is an associate professor of gerontology and geriatric medicine at the Wake Forest School of Medicine. She is interested in the relationships between the brain and aging-related changes in metabolism and movement. The natural course of aging can change the way the body uses fats and sugars and increase the risk for obesity and type 2 diabetes. Aging also increases the risk for slower gait and the chances of falling. Healthy exercise and eating can help preserve and recover both cognitive and physical function as people age. Her lab is interested in studying the effects of various lifestyle choices on both the body and the brain in aging, to help people live fulfilling lives.

CHRISTINA T. SORIANO

Christina is the vice provost of the arts at Wake Forest University and an associate professor of dance. She studies the ways movement and dance can improve the mobility, balance, cognition, and quality of life of older adults living with diseases like Parkinson's and Alzheimer's. She is fortunate to do this work with a brilliant neuroscientist, also named Christina, who is also a co-author of this paper!

JENNIFER L. ETNIER

Jenny is a distinguished professor and the chair of the Department of Kinesiology at the University of North Carolina at Greensboro (UNCG). Before joining UNCG, she received her degrees from the University of Tennessee (B.S.), University of North Carolina-Chapel Hill (M.A.), and Arizona State University (Ph.D.). Jenny has over 80 publications in the fields of exercise sciences and cognitive psychology and also wrote the book *Bring Your "A" Game: A Young Athlete's Guide to Mental Toughness*. Jenny and Shin have been working on developing music-based exercise programs for middle-aged and older adults with and without medical conditions.

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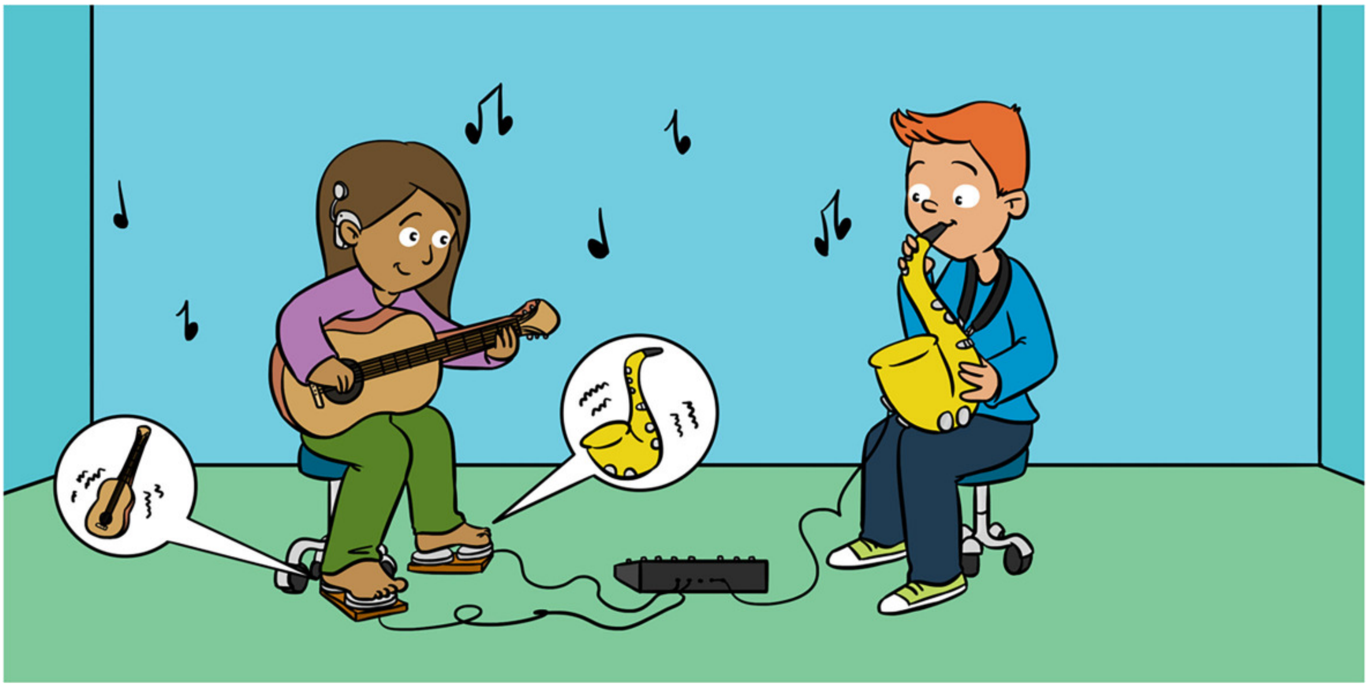

DEAFNESS AND MUSIC: CAN VIBRATION BE USED WHEN PLAYING MUSIC TOGETHER?

***Carl Hopkins*[1*], *Saúl Maté-Cid*[1], *Robert Fulford*[2], *Gary Seiffert*[1], *Jane Ginsborg*[2] and *Natalie Barker*[1]**

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YOUNG REVIEWER:

ALEX

AGE: 11

Performing music or singing together provides people with great pleasure. But if you are deaf (or hard of hearing) it is not always possible to listen to other musicians while trying to sing or play an instrument. It can be particularly difficult to perceive different musical pitches with a hearing aid or other hearing-assistance device. However, the human body can transmit musical sounds to the brain when vibrations are applied to the skin. In other words, we can *feel* music. Our research has identified a safe way for deaf people to hear musical notes through the skin of their hands and feet. We have shown that vibration allows people to safely feel music on the skin. This approach allows people to identify a musical note as being higher or lower in pitch than other notes, and it helps musicians to play music together.

INTRODUCTION

The classical composer Beethoven composed some of his finest music when he was extremely deaf. How did he do this? It is said that he put a wooden stick between his teeth and pushed it against the piano to feel the vibrations. Dame Evelyn Glennie is a famous percussionist who happens to be deaf. When practicing and performing, she can feel the vibrations generated by her instruments.

COCHLEAR IMPLANT

An electronic device inside the inner ear that helps a deaf person to hear.

Many adults who use hearing aids or **cochlear implants** have difficulty listening to music [1]. For adult musicians and singers who have hearing impairments, deafness can make it difficult to take part in music making [2]. There are 32 million deaf children in the world, so could vibration help them learn to play instruments and perform with other children? Our research investigated the range of musical notes that can be felt safely using vibration, and whether people can tell the difference between notes felt through vibrations.

CAN WE HEAR THROUGH THE SKIN?

Our ears convert sounds into signals that are sent to the brain so we can identify them. The outer part of the ear—the soft part on the outside of the head—is called the pinna. The pinna helps sound enter the ear canal, which is a short tube that leads to the eardrum in the middle ear. The sound makes the eardrum vibrate. These vibrations are sent to the cochlea in the inner ear by the vibration of very small bones. Inside the inner ear, there are tiny hair cells that are sensitive to vibration, and they convert the vibration into electrical signals to be sent to the brain. Hair cells are called **mechanoreceptors** because they are receptive to mechanical vibration.

MECHANO-RECEPTORS

Sensors in the body that respond to mechanical pressure or change of shape.

When we feel vibration, signals are sent to the brain by different kinds of mechanoreceptors that are underneath the top layer of the skin. These mechanoreceptors are not as sensitive as those in our ears, but they allow us to feel vibration for some sounds that can be heard with our ears.

CAN WE SAFELY APPLY VIBRATION TO HANDS AND FEET?

Very loud sounds can damage the ears, so is vibration safe? When workers dig up roads using a pneumatic drill, they are exposed to high levels of vibration. This can cause a permanent health problem called hand-arm vibration syndrome that makes a person's fingers feel numb. To avoid this problem, we investigated whether a person could feel musical notes at low levels of vibration that were safe over a long period of time. This is important because musicians and singers spend many hours practicing their instruments. We used experiments to find

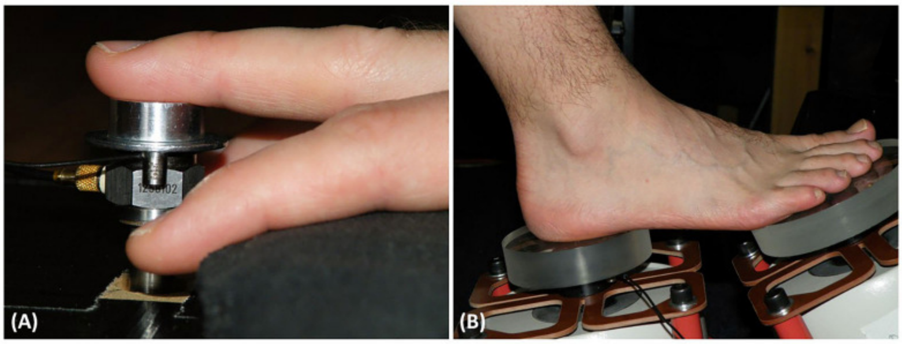

Figure 1

Figure 1

Contact discs for **(A)** the fingertip, and **(B)** the heel and forefoot. Both are connected to electrodynamic shakers that make the discs vibrate so that the user can feel the vibrations through the skin.

Figure 2

Figure 2

Musical notes on a piano keyboard. The notes within the red box can be used for the vibrotactile presentation of music. The higher notes, from A5 onward, are more difficult to feel. This indicates that the sense of hearing is more sensitive than the sense of touch.

the lowest levels of vibration that people could feel on their fingertips and the soles of their feet [3]. This was done for different musical notes. These lowest levels are called **vibrotactile thresholds**. *Vibro* indicates vibration, *tactile* indicates the sense of touch, and *threshold* refers to the lowest level.

Why did we use the hairless skin on the palms of the hands and the soles of the feet? Because this skin is more sensitive than hairy skin, and therefore has a lower vibrotactile threshold. We thought that singers could use their fingertips to feel the vibrations caused by other musicians. However, musicians playing instruments with their hands would need to use their feet to feel the vibrations. To provide the vibration, we used a flat disc that contacts the hand or the foot, connected to a device called an electrodynamic shaker (Figure 1). Shakers are similar to loudspeakers, but instead of producing sound, they only make vibration. A loudspeaker is fragile and is easily damaged so it can not be touched, but a shaker is robust and can support the weight of a hand or foot.

In traditional Western music, a **musical scale** has seven notes. For example, the scale of C major contains the following notes: C, D, E, F, G, A, B. Each note has a different **pitch**. You might remember the sound of these seven notes if you have ever sung the "Do-Re-Mi" tune because they are equal to "Do," "Re," "Mi," "Fa," "Sol," "La," "Ti." In Figure 2 you can see that these are the white notes on a piano keyboard. This sequence of notes is repeated across the entire keyboard, where the next C is an **octave** higher in pitch. To name the notes in different octaves, a number is added after each note. For example, G5 refers to G in octave 5.

VIBROTACTILE THRESHOLD

The lowest level at which a person can perceive vibration through touch.

MUSICAL SCALE

A group of notes arranged in order of their pitch.

PITCH

The lowness or highness of a note.

OCTAVE

The interval between two notes where one note has twice or half the frequency of vibration of the other.

Our experiments showed that all musical notes from C1 (low pitch) up to G5 (high pitch) can be felt clearly on hands and feet. Importantly, these notes could be felt at a safe level that avoided health problems. This range of notes covers more than four octaves, which includes most notes on a piano (Figure 2) and on many other instruments, as well as notes produced by the human voice. The fact that people have more difficulty feeling the high notes from A5 to C8 on the piano reminds us that the sense of touch is less sensitive than the sense of hearing.

For low-pitched notes, we found that the heel and the forefoot had lower vibrotactile thresholds than the fingertip. Most musicians can not use their fingertips while they are playing an instrument, so it is helpful that their feet are more sensitive, and they can use those to detect vibrations. We also found that the vibrotactile threshold for fingertips is similar for people with normal hearing and people who are deaf. This means that vibration could be used by everyone.

CAN WE TELL THE DIFFERENCE BETWEEN MUSICAL NOTES USING VIBRATION?

RELATIVE PITCH

The ability to correctly recognize or produce a musical note in terms of its relative position in a musical scale.

Identifying **relative pitch** is a useful skill for musicians. This means they can identify or sing a musical note after they have heard another note. Think about the "Do-Re-Mi" tune again. If you heard "Do" followed by "Mi" and had relative pitch skills, you would be able to say that "Mi" was a higher pitch than "Do." We carried out experiments with vibration to see if it was possible to identify one note as being higher or lower in pitch than another note when using the fingertip or forefoot [4]. The musicians with normal hearing carried out 16 short training sessions to see if they could improve their skill.

INTERVAL

The distance in pitch between two notes.

We found that wide pitch **intervals** were easier to identify than narrow intervals. A wide interval has notes that are far away from each other, such as from C to G. In a narrow interval, the notes are close together, such as from C to D. In terms of "Do-Re-Mi," it was quite easy to tell "Do" from "Fa," "Sol," "La," and "Ti" but harder to tell "Do" from "Re" or "Mi." This happened with amateur and professional musicians with normal hearing as well as professional musicians with a hearing loss. The short training sessions improved the relative pitch skill of the musicians with normal hearing.

HOW CAN VIBRATION BE USED TO PERFORM AND LEARN ABOUT MUSIC?

Musicians can use vibration to help them learn an instrument and play music with other people, by sending the sound from each instrument to a mixing desk and then sending it back as vibration to the musician's

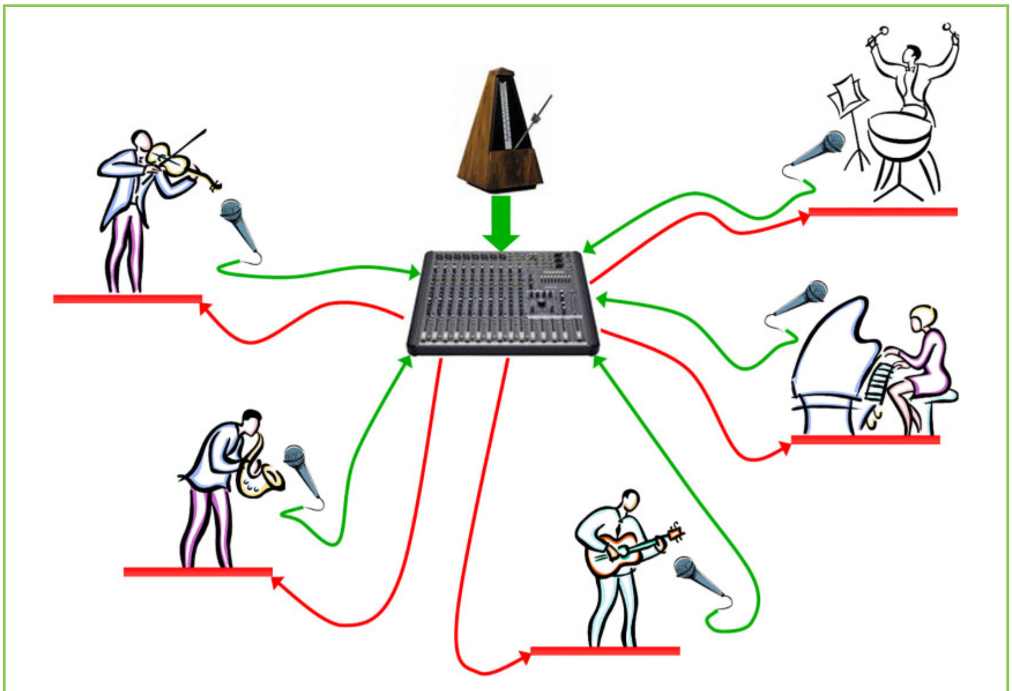

Figure 3

Group musical performance using vibration. Green lines show sound picked up by microphones and taken to the mixing desk. Red lines indicate the "mixed" signal sent as vibration to the musician's feet.

body (Figure 3). For example, a guitarist could choose to feel the drums on one foot and their own guitar on the other foot.

Our equipment was installed in the Royal School of the Deaf Derby. **Video 1** shows the responses of staff and pupils who used the vibrotactile equipment to understand musical pitch and play music together in their lessons [5]. The music teacher, Matthew Taylor, found that the equipment made a positive change to his teaching and that it created a calmer atmosphere in the classroom. Matthew used the equipment to help his students make a connection between vibration and the pitch of a note. This helped the students decide if one note was higher or lower than another note. Matthew said that his students became more interested, independent, and active in music lessons, and that they really enjoyed playing music together.

VIDEO 1

Video showing the responses of staff and pupils at the Royal School for the Deaf Derby who used the vibrotactile equipment in their music lessons.

CONCLUSIONS

Our research shows that vibration can be used at a safe level by people with hearing impairments to help them play music with other musicians. We hope this technique will provide more opportunities for children and adults with hearing impairments to perform, enjoy, and compose music. The research promotes inclusive music education by making music more accessible to children with hearing impairments.

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comply with these terms.

YOUNG REVIEWER

ALEX, AGE: 11

I like to play baseball and tennis. I like to go fishing anywhere, especially in FL. I also fly fish and like camping in the Rocky Mountains in CO. My favorite book series is the Spy School series and favorite colors are green and blue. Math and Science are my favorite subjects. I have one dog, one turtle, and twelve fish.

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frontiers FOR YOUNG MINDS

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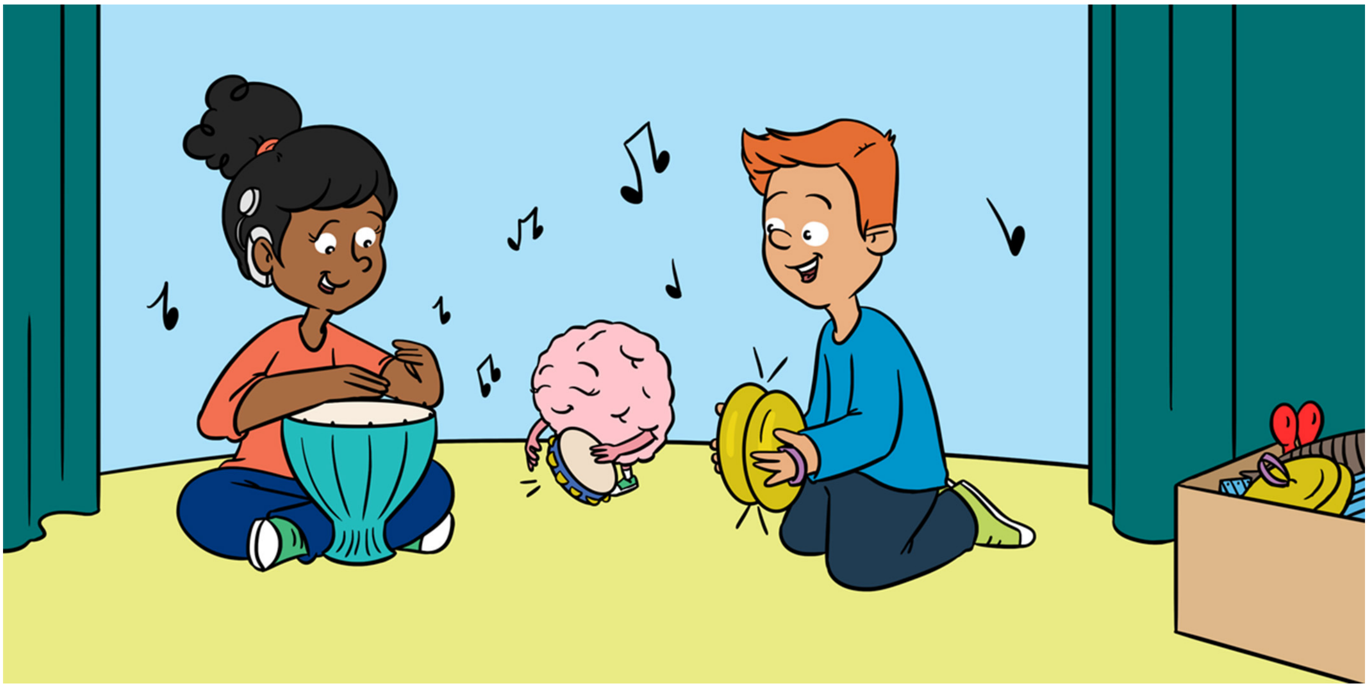

CAN MUSIC TRAINING IMPROVE LISTENING SKILLS FOR CHILDREN WITH HEARING LOSS?

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YOUNG REVIEWERS:

AARON
AGE: 11

ISLA
AGE: 9

Hearing aids and cochlear [**ko**-clear] implants are very useful devices for children with hearing loss. But they do not completely restore hearing. Many children with hearing loss find it difficult to listen in noisy places like the playground. This is important because many social interactions create noise or occur in noisy places. While most people think we listen through our ears, it is the brain that does most of the hard work! We thought that music training might be a good way to improve listening skills. Why? Because music is a fun activity that involves not only sounds, but also sights, movement, memory, and more! This means a lot of activity and learning, which is good for the brain. What did we find? After 12 weeks of music training, children with hearing loss were better at listening, particularly in noisy environments.

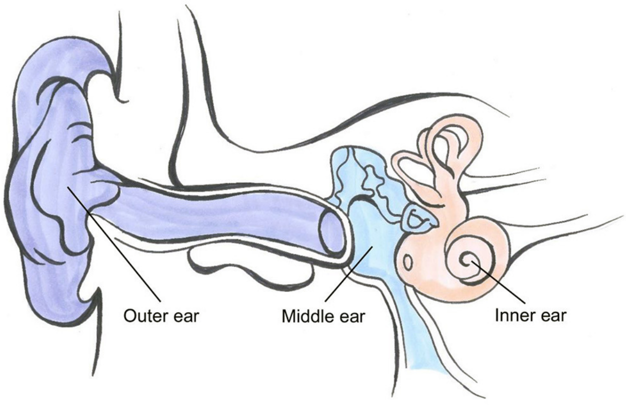

Figure 1

Figure 1

The hearing pathway. Sound is collected by the outer ear; the middle ear amplifies sound (making sound louder); and the inner ear transforms sound into electrical signals, which travel to the brain. Finally, the brain gives meaning to these electrical signals.

GOOD VIBRATIONS

Did you know that sound is made by objects vibrating? When you hear a person speaking, you are hearing the vibrations of their voice traveling through the air as sound waves. Try resting your hand gently on your throat and say, "bees buzz loudly." Did you feel your throat vibrate? These vibrations are made in your voice box, or larynx [**la**-rinks].

Sound made by people or objects pass through the air and into your ears. Ears are made up of three sections. The outer ear collects and funnels sound; the middle ear amplifies sound, which means it makes sound louder; and the inner ear transforms sound into electrical signals, which travel to the brain. Finally, the brain gives meaning to these electrical signals. This is how we understand or perceive sound. This whole process is called the **hearing pathway** (Figure 1). You might be surprised to learn that your brain, not your ears, is the most important part of hearing! Your brain lets you hear all sorts of sounds like waves crashing at the beach, laughter, and songs. What are your favorite sounds, and what do they mean to you? Is music your favorite sound? Did you know that learning music can help people with hearing loss?

HEARING PATHWAY

How sound travels from the ear to the brain and is given meaning.

HEARING LOSS

A problem at some point in the hearing pathway that usually means hearing difficulties.

DID YOU HEAR THAT?

Hearing loss occurs when there is a problem at some point in the hearing pathway. A child with a *mild* hearing loss might have difficulties with soft sounds like whispering. Someone with a *profound* hearing loss might only be able to hear very loud sounds, like a jet engine or an emergency siren.

Hearing aids and **cochlear implants** are commonly used to improve hearing loss (Figure 2). Hearing aids pick up sound with a small microphone. These sounds are amplified and come out of a

HEARING AID

An assistive listening device that amplifies sounds.

COCHLEAR IMPLANT

An assistive listening device that bypasses the outer and middle ear, and sends electrical signals to the inner ear. Sometimes known as the bionic ear.

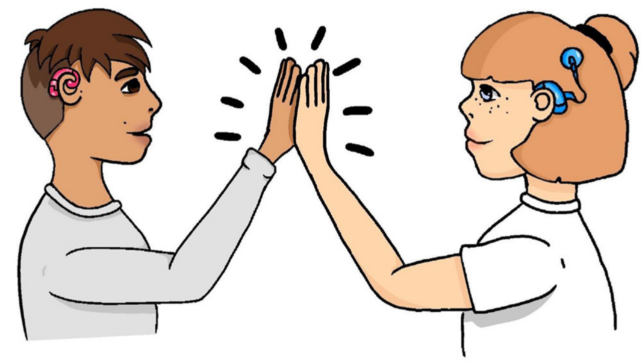

Figure 2

Figure 2
The child on the left uses a red hearing aid. Hearing aids work by making sounds louder. The child on the right has a blue cochlear implant. Cochlear implants work by sending electrical signals directly to the inner ear.

miniature loudspeaker into the ear. Hearing aids work like headphones and mostly make sounds louder. But cochlear implants work very differently. They pick up sounds and send electrical signals directly to the inner ear. Some adults describe the cochlear implant as sounding tinny, robotic, and electric [1]. Fortunately, the brain has an extraordinary capacity to adapt! So, people find that these devices sound better with time, effort, and experience.

Hearing aids and cochlear implants are very useful devices. But they are not like glasses that make everything clear and readable when you put them on. Many children who use hearing aids or cochlear implants find it difficult to listen in noisy places. This can be a huge problem, especially because we often need to talk in noisy environments. Think about how noisy it gets during a class discussion, chatting with your friends in the playground, at a birthday party, or at a busy restaurant. Imagine how much you would miss if you could not hear well in those situations.

MUSIC TO YOUR EARS, BUT MOSTLY FOR THE BRAIN!

Musical activities use lots of brain power! Imagine you are playing the piano. As you read the sheet music in front of you, your eyes tell your fingers which keys to play. Each key you play creates sound, and your ears and brain provide feedback about whether you have played the correct notes. You might be able to play a song by memory, and you can even make up your own song. You can invite other musicians to form a band and play together. All these aspects of music provide the brain with a complete workout—one that relies on sound, vision, memory, creativity, social skills, and more!

The most common way to explore the benefits of music is to look at the differences between professional musicians and someone with little or no musical training. An important discovery is that professional musicians are better at listening in noisy environments than non-musicians are [2]. This means that they are good at hearing what people are saying at a party and they can ignore all the background noise. How do musicians gain this skill? Some may have been born with good listening skills, which could have made them more likely to enjoy music in the first place [3]. But others may have learned to listen better through years of practice. One study showed that children improved their listening skills after 2 years of music training [4]! So, like most things, your ability to listen in noisy environments probably has something to do with natural talents *and* lots of practice [5]. You can learn more about music in the brain in this *Frontiers for Young Minds* article, and this one [6, 7].

EXPERIMENT TIME, WHAT DID WE LEARN?

Scientists are only just beginning to understand how music might help children with hearing loss. To explore this, we studied 14 children (between 6 and 9 years of age) with hearing loss, both *before* and *after* they received music training. To keep things fair, we only selected children who were born with a moderate to profound hearing loss and who were using hearing aids and/or cochlear implants.

How did we measure listening skills? We asked each child to listen to twenty different sentences such as: "They broke all the eggs"; "Children like strawberries"; or "The clown had a funny face". The tricky part was that four other voices were also talking in the background, which made things pretty noisy! Every time a child repeated most of the sentence correctly, the noise would become louder. This made the next sentence more difficult to hear. If the child got most of the sentence wrong, the noise would become softer, making the next sentence easier to hear. After doing this 20 times, we calculated each child's **speech-in-noise score**. A good speech-in-noise score means that a person can understand speech even when surrounded by lots of loud noise.

SPEECH-IN-NOISE SCORE

A score of how well a person can listen in noise.

To measure our children's musical skills, we used a test of **timbre** [**tam**-ber]. Timbre is how we describe instruments or voices sounding different, even if they are playing the same song at the same speed and volume. Some people like to think of timbre as describing the *texture* of sound. For example, if you played "Happy Birthday" on a xylophone, it would have a different timbre than if you played it on a harp, or if you sang it. It is timbre that lets you know which instrument is which. In this test, the children had to identify which instrument was playing a short tune. There were eight possible instruments to choose from: piano, violin, cello, acoustic guitar, trumpet, flute, clarinet, and saxophone.

TIMBRE

How we describe the different sounds of instruments or voices, even if they are playing the same song, pitch, or melody.

Before the children started music training, we measured their listening and musical skills. twice-12 weeks apart. This baseline measurement result showed that, after simply living their lives as usual, there was

Figure 3

Figure 3

The music training that the children in our experiment received included **(A)** playing and listening to percussion with blindfolds on, and **(B)** playing together as a band.

no change to any of their skills. The children did no training, and their listening skills did not improve.

After this baseline test, the children began a 12-week course of music training. They joined other children for music therapy such as drumming, singing, and dancing together (Figure 3). They also played musical apps on smart phones or tablets in their own time. These included "drawing" songs, or matching sounds to instruments. At the end of the 12 weeks of music training, we measured the children's musical and listening skills again. And this time, we found some improvements!

We discovered that children who had completed the training were better at listening to speech in a noisy environment, which was what we were hoping for! The children were also better at identifying various instruments and perceiving timbre. Timbre gives us an important clue about *why* the children improved in their abilities to listen in noisy environments.

Imagine you are in class, trying to listen to your teacher on a noisy day. There might be all sorts of unwanted, distracting sounds around you. Other children are speaking, footsteps echo through the hallway, students type on keyboards, and laughter from the playground leaks through the window. All these sounds can add up together to become noise. To focus on your teacher's voice, your brain needs to identify which sounds you want to listen to and which sounds are noise that you want to ignore. Timbre perception helps you do this. You can learn more about separating sounds in this *Frontiers for Young Minds* article [8].

Parents of the children also noticed improvements. One said: "We would like to continue with the music program, as our son has made significant progress in the 12 weeks, and we would love for him to go further again! We have noticed that he has become quicker to identify songs on the radio. Even more astounding is that he has suddenly developed some intonation and tune to his singing along, which was previously non-existent."

ALL TOGETHER NOW!

Hearing aids and cochlear implants are amazing devices that help restore *some* hearing, but not all of it. A common difficulty for children with hearing loss is listening and interacting in noisy environments. It is important to explore ways to improve this skill, as the world can be a very noisy place! We thought music would be a good activity to investigate, as music generates a lot of brain activity. As you now know, the brain is where the most critical part of hearing occurs. After 12 weeks of music training, the children with hearing loss were better at listening in a noisy environment. We hope this will help children with hearing loss live happier lives in noisy and important places like the classroom and playground!

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ORIGINAL SOURCE ARTICLE

Lo, C. Y., Looi, V., Thompson, W. F., and McMahon, C. M. 2020. Music training for children with sensorineural hearing loss improves speech-in-noise perception. *J. Speech Lang. Hear. Res.* 63:1990–2015. doi: 10.1044/2020_JSLHR-19-00391

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CONFLICT OF INTEREST: CL is currently employed as a consultant for Cochlear Limited. VL was previously employed by Advanced Bionics. However, Cochlear Limited and Advanced Bionics have had no input into any part of this study or this article.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

AARON, AGE: 11

Aaron is 11 years old and likes going on skiing holidays. He loves computer games and sports. His faourite subjects are maths (sometimes!) and P.E. His dream place to visit would be Italy because it has all the things he loves: really good food, beaches, and the alps for skiing. Aaron and Isla are brother and sister. They live in Scotland and love playing and annoying each other! They have great imaginations and are fantastic at coming up with new experiments.

ISLA, AGE: 9

I love rainbow belts and food. I have an annoying brother, Aaron. I love Hamilton, trampolining, my teddies, and my best friends. My personality is drama. I would love to go to America because it has amazing sweets. I care for my friends and family. My favorite subject is art I want to be a painter in houses when I am older and have a room in my own house where I can paint on the walls and discover new designs.

AUTHORS

CHI YHUN LO

I am a research fellow at the Australian Institute of Health Innovation, an adjunct fellow at Macquarie University in Australia, and the committee secretary of the Parents of Deaf Children. Communication is central to what makes us human, and I find the act of listening wonderful and intriguing! I am interested in the role of music in the lives of people who are deaf and hard-of-hearing. Before studying to become a researcher, I was a musician and audio engineer, making and mixing sounds. So, it is probably no surprise that I will always find time for music! *chi.lo@mq.edu.au

VALERIE LOOI

I am an audiologist, music therapist, and researcher who specializes in researching how adults and children with cochlear implants (CIs) and hearing aids hear music, and how this could be improved. I used to work for two CI companies where I managed their research across all of the Asia-Pacific region, but I am now the general manager for Advance Healthcare. However, I continue to help with research related to music for those with CIs or hearing aids, and particularly music training to help improve music listening, because it is a big passion of mine to help people with hearing loss enjoy music more, and to get better at it.

WILLIAM FORDE THOMPSON

I am director of the Music, Sound and Performance Laboratory and a distinguished professor at Macquarie University, Sydney, Australia. I became interested in music as a child growing up in Canada, where I spent hours every day making up new sounds and melodies on the piano, and driving my parents crazy. Music became a "friend" to me, and eventually I found other kids who had the same friend! I believe music can benefit all people, making us feel good and helping us understand ourselves and others. In my research, I want to find out why music is so powerful.

CATHERINE M. MCMAHON

I am a professor of audiology at Macquarie University in Australia. I work in the Australian Hearing Hub with many researchers and teachers, innovators who develop hearing technologies, and specialists who work with people who have hearing loss. I spend much of my time doing interesting research with individuals and communities in Australia and overseas to improve the ways that we all can take care of our hearing. I also teach university students to become great audiologists, so they can measure hearing levels and fit hearing aids and cochlear implants for babies, kids, and adults who have hearing loss.

HUMAN HEALTH
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HOW DEAF KIDS HEAR MUSICAL HARMONY THROUGH A COCHLEAR IMPLANT

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YOUNG REVIEWER:

FLORENCE

AGE: 8

With cochlear implants, you can make it possible for deaf people to hear again. The people who developed theses cochlear implants were mainly interested in enabling the deaf people to understand what other people say. In this study, we asked ourselves how good a cochlear implant is when listening to music. We worked with children born deaf who have never heard without a cochlear implant. For music, an exact hearing of tones played at the same time is necessary to understand the logic of a lot of music. We call this logic musical harmony. We found that deaf children with cochlear implants are not so different to normal-hearing children when listening to harmony of single notes. However, when listening to tunes they have more difficulties. Thus, understanding music through a cochlear implant seems to be more challenging than understanding speech.

INTRODUCTION

Have you ever heard somebody playing a tune on a piano? It is likely that you can easily notice when a piano player hits an incorrect key, because it sounds weird. This is possible even if you are hearing the song for the first time, or even if you do not play the piano yourself. Also, you can probably notice when music arrives at a logical pausing point. You might compare it to the end of a sentence, or the end of a line in a poem. This means that you notice some sort of musical grammar, even without being aware of it.

Now imagine a child who has been deaf since birth or early childhood. Unaided, deaf children cannot hear a honking car horn or listen to music, and they cannot communicate with family and friends using spoken language. In most of these children, some hearing can be restored by inserting a device called a **cochlear implant (CI)** into the inner ear (Figure 1). This device triggers the nerve that connects the inner ear to the brain. Although the way the device transfers sounds is somewhat coarse, most CI users understand speech very well. Think about a blurred photo of your family, in which you can still recognize your parents.

COCHLEAR IMPLANT (CI)

An electronic device that brings back hearing to deaf people. By surgery through the skull, it is positioned at the hearing nerve connecting the inner ear to the brain.

HARMONY

The musical logic how notes are combined to chords and chords to meaningful music.

We wanted to know if CI users sense musical **harmony** similarly to the way normal-hearing people sense it [1]. Music helps with skills including learning a language, reading, and understanding math. Thus, if CI users sense musical harmony in a similar way normal-hearing people do, it is likely that music can have the same positive effect on their development of these skills.

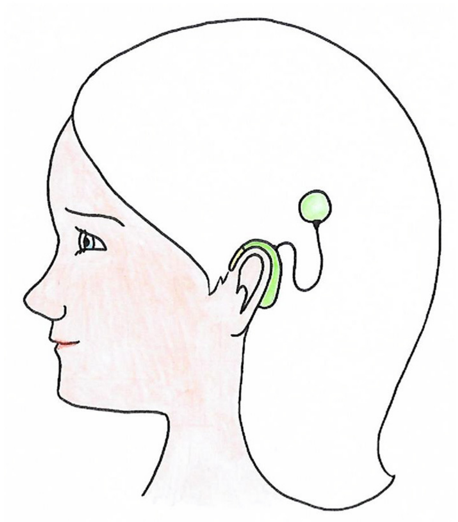

Figure 1

Figure 1

A child with a CI. The earpiece contains three important things: batteries, a microphone, and a processor that calculates the electric impulses needed to trigger the nerve. The information is then delivered through the cable to a coil (the round thing on the head). The coil gives the information to a receiver, which is deep inside the ear, and cannot be seen from the outside. From there, a cable leads into the inner part of the ear and releases the electric impulses to create the impression of a sound.

WHAT WAS OUR EXPERIMENT?

To understand how CI users perceive sounds and how sound heard using a CI compares to normal hearing, we invited CI users and normal-hearing people to participate in our listening experiments. We designed these experiments to test certain aspects of how people hear sounds. In an earlier study, we investigated how music is heard by adults who grew up with normal hearing but lost their hearing later in life [2]. For these listeners, the music experience they gained before their hearing loss might affect how they sense music with a CI. In contrast, our 12 CI users were all born deaf or lost their hearing early, so they could not develop any musical knowledge before they received a CI. The CIs were inserted into their ears at about 1–2 years of age. We also tested 24 normal-hearing children to understand how well children performed our experimental tasks when they listened with their own ears.

In our experiments, we examined how the children with CIs and the normal-hearing children experienced musical **chords**. Musical chords are assembled from several tones played at the same time, like when certain piano keys are pressed together. Depending on which tones are combined, some chords give a pleasant and soothing (**consonant**) sensation. If you play a piano, you might know this impression from the combination C-E-G, a so-called major chord. It sounds particularly clear and solid. If you instead play C-E-G sharp, it sounds quite scraping and tense. Such chords generate an unpleasant and disturbing (**dissonant**) sensation.

CHORD

Combination of musical notes played at the same time.

CONSONANT

Sounding pleasant or soothing.

DISSONANT

Sounding unpleasant, rough or disturbing.

Our first question was whether CI users and normal-hearing people prefer the same types of chords. Most normal-hearing people prefer pleasant/consonant chords to unpleasant/dissonant chords. We selected four of the most common chords. Two of them were pleasant/consonant chords (the first one was in fact the major chord). The other two chords were unpleasant/dissonant. Listen to these four chords in **Video 1**. The chord sounds were presented in pairs. After each presentation, our listeners had to choose the more pleasant sound from the pair.

VIDEO 1

First, there are the four sounds from experiment 1: consonant 1, consonant 2, dissonant 1, and dissonant 2. In each trial, two sounds should be compared. Starting from 00:25, there is a song example from experiment 2 in two versions: the first one ends with an odd, improper final sound. From 00:39 on, the sound is played again, ending with the correct sound.

Our second experiment tested whether CI users noticed a musically expected ending, the way you notice when a sentence ends. We selected eight different tunes known to the children in our country (Germany). You might know some of them, like "Happy Birthday" or Brahms' "Lullaby." The tunes were played in three variations: the original one (musically correct) and two modified versions, with the last chord exchanged for an unpleasant one. After each presentation, our listeners had to decide whether the ending of the tune was fine or odd-sounding.

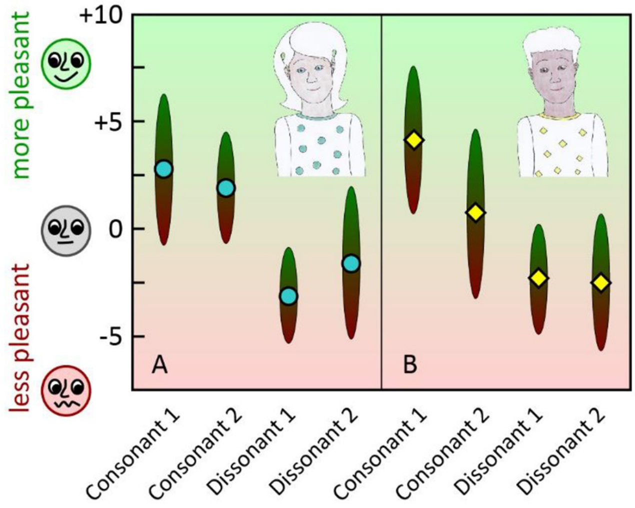

Figure 2

Figure 2

(**A**) Light blue dots show the average preferences of the CI users for single chords. (**B**) Yellow diamonds show the average chord preferences of the normal-hearing children. In both panels, the long ovals show how much the different listeners vary. The colors in the background show intensity: the greener the green color gets, the more the chord is favored. The redder the red color gets, the more the chord is disliked. These results show that CI users prefer the same chords the normal-hearing children.

WHAT DID WE FIND?

Figure 2 shows the results of our first experiment. The normal-hearing children preferred the consonant chords. The two dissonant chords were less favored. This is what we expected, based on musical theory. Results from CI users look rather similar to those of the normal-hearing children. CI users preferred the same chords, consonant 1 and 2, over the two other, dissonant chords.

In the second experiment, our listeners had to decide if the song endings sounded fine or odd (Figure 3). The data show that normal-hearing children had no problem with the task—in fact, in most cases, their performances were close to perfect. Only our two youngest listeners showed less-than-perfect performance, but they were only 5 years old. In contrast, CI users could not distinguish between an ending that is odd and one that is expected. CI users also did not get better at this task with age.

WHAT DO OUR RESULTS MEAN?

The results of our first experiment show that the sound processed through a CI is precise enough to sense how good/consonant or bad/dissonant a chord sounds. The preferences of CI users are very similar to those of children with normal hearing. These results show that a CI should provide the information necessary to experience this aspect of music. However, in our second experiment, none of the CI users could distinguish an odd-sounding ending from a normal-sounding one, whereas nearly all the normal-hearing children did so with ease. As mentioned before, we did a similar study with grown-ups who had lost their hearing later on in life, and thus had the chance to listen to music with their own ears before receiving

Figure 3

Each diamond shows the result of a normal-hearing child. The further to the right the diamond is, the older the child. Each dot stands for a child with a CI. Instead of age, the horizontal positions of the dots show the time since the child got the CI. The greener the background, the better they could tell the song endings apart. The redder the background, the less they could perform the task. Perfection is shown by the upper dotted line. You can see that most normal-hearing children scored close to perfection, but all CI users reached very low scores.

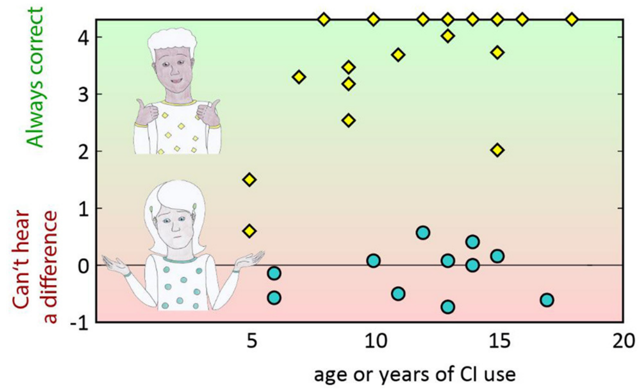

Figure 3

CIs [2]. These listeners also could not tell odd and normal-sounding endings apart from each other. We found the same result in our group of CI users who never had the chance to listen to music with their own ears. This result implies that distinguishing normal-sounding vs. odd-sounding song endings is a specific problem of listening through a CI and does not depend on having listened to music naturally in the past.

A group from France [3] used sung melodies with chords (some with odd endings and some with expected endings) and measured the time listeners needed to figure out what syllable the singer was pronouncing. In such a task, normal-hearing listeners usually react faster to expected endings. This is because people are usually slowed down by disturbances like unexpected sounds. Surprisingly, the researchers found that CI users, reacted faster when the last chord was a musically odd one. They concluded that the CI users recognized the difference between expected endings and odd endings, because their reaction times changed with the type of ending. The fact that CI users were faster when the last chord was musically odd suggested that they did not find the dissonances disturbing. Remember our initial comparison to looking at a blurred family photo? Imagine that the picture contains enough information to recognize the people in it, but it is too blurred to decide if they are happy or sad. In the same way, CI users miss a part of the emotion of the music.

What if children with CIs just need more time to learn? We did not find any tendency toward improvement in these tasks in older children. Nevertheless, we cannot rule out this possibility. Maybe specific listening training, focusing on aspects of music, could help them. This is a question that researchers are working on now.

CONCLUSION

In many children who are born deaf, CIs can restore their hearing well enough that they can understand speech. Our study shows that understanding music through a CI seems to be more challenging than understanding speech. The ability to tell whether a single musical chord sounds nice or weird, in the same way that normal-hearing people do, does not seem to be enough to allow a grasp of musical grammar. We do not believe that it is impossible for CI users to perceive this aspect of music. Focused music training may help CI users to learn how a normal song ending sounds. It is also possible that progress in CI technology will improve the way music is transmitted to CI users. For instance, researchers are trying to understand how the notes in a chord interact through a CI. It would be nice if future CI users could sense musical grammar the same way normal-hearing people do, because only then will they be able to grasp the musical "jokes" and false endings that Mozart and others loved to hide in their pieces!

ORIGINAL SOURCE ARTICLE

Zimmer, V., Verhey, J. L., Ziese, M., and Böckmann-Barthel, M. 2019. Harmony perception in prelingually deaf, juvenile cochlear implant users. *Front. Neurosci.* 13:466. doi: 10.3389/fnins.2019.00466

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWER

FLORENCE, AGE: 8
Hi my name is Florence and I am 8 years old. I am really into art and reading. I have 7 dogs and 3 cats. My favorite activity is horse riding.

AUTHORS

VICTORIA ZIMMER
I am an aspiring ophthalmologist and I started examining deaf people when I was still in medical school. I was so fascinated by cochlear implants that I conducted the study described in this article with my colleagues, for my doctoral thesis. I also worked for some time in a psychiatric hospital with hearing-impaired children, and I learned how to use sign language. Even my hobbies involve seeing and hearing: I am into handcrafts and making music.

JESKO LARS VERHEY
My mum was singing in a choir and always had to practice at home when I was a child. That was probably what sparked my early interest in hearing. I am currently a professor at the Otto von Guericke University Magdeburg (Germany) and my interest is understanding not only normal hearing but also what changes when a person's hearing is impaired. Cochlear implants are fascinating devices that can give the hearing experience back to deaf people. I want to know how deaf people with cochlear implants perceive sounds, compared to people with normal hearing.

MARTIN BÖCKMANN-BARTHEL
As a senior researcher, I study how the brain processes sound. With my colleagues, I have investigated how a mixture of sounds separates into different sound sources. I am interested in cochlear implants because they are a great technique for helping deaf people to hear, and I specifically want to understand why music is processed less precisely than speech. Apart from science, music is also an important part of my life, like singing in small choirs and going to concerts. I also like distance running and going on hikes. *martin.boeckmann@med.ovgu.de

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HOW VOICE ANALYSIS CAN HELP SOLVE CRIMES

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YOUNG REVIEWERS:

RYAN
AGE: 15

WILLOW
AGE: 13

Imagine you are a police officer investigating a crime in which somebody has made a threatening phone call. There may not be any physical evidence like DNA or fingerprints, but the person's voice is captured on a recording. Experts can analyze the voice recording and compare it with the voice of a known suspect to find out how likely it is that they are the same person. This method is called forensic voice comparison. It works because people's voices contain lots of information about them. Your voice tells a story about where you grew up and learned to speak, and your voice also depends on your individual biological make-up. In this article, we explain how this information is used to compare recordings of voices in criminal cases.

HOW YOUR VOICE WORKS

Imagine that a criminal has made a threatening phone call, and the police have a recording of the call but do not know who made it. The voice in the recording can be compared to the voices of suspects, to try to identify the criminal. This process is called **forensic voice comparison** [1].

FORENSIC VOICE COMPARISON

The use of scientific techniques to determine how likely it is that speech samples came from the same person, to help in criminal investigations, and other legal matters.

FREQUENCY

The number of vibrations per second in a sound wave. High notes have a high frequency and low notes have a low frequency.

To understand forensic voice comparison, we need to understand how sound and voices work. All sound is made up of vibrations in the air, and the **frequency** of a sound is how fast it makes the air vibrate. We hear low frequencies as low pitches and high frequencies as high pitches, but most natural sounds contain lots of frequencies that give us additional information—for example, a violin and a piano playing the same note sound different because they contain other frequencies as well as the pitch.

When we speak, sound is produced by the vocal cords, which are two small, vibrating muscles in your throat. The vocal cords make a buzzing sound, and how fast they vibrate determines the pitch of your voice. To turn the buzzing sound into speech, you also need the vocal tract, which is the name for the flexible tube between your vocal cords and your lips. To make specific speech sounds, you change the shape of this tube by moving what are called your articulators: your tongue, jaw, and other parts of your mouth. This changes the frequencies that are present in your voice [2].

Try it now: start by humming and place your hand on your throat. You should feel a vibration, caused by your vocal cords. While you are humming, your mouth is closed—your articulators are in the position used to produce the sound "m." Now, while still humming at the same pitch, open your mouth. It will sound like "ma" as your articulators move from the position for "m" to the position for "ah." You did not change the pitch of your voice, but by changing the shape of the vocal tract, you changed the other frequencies that were present, resulting in different speech sounds.

People's voices are different from each other for two reasons: *biological* differences in the size and shape of their vocal cords and vocal tracts, and *behavioral* differences in how they have learned to use their voices. For example, larger people will have bigger vocal cords, giving them lower-pitched voices. They did not learn this, it is just a result of their size. Alternatively, people with different accents might pronounce words differently. An English person might say "down" or "daan," but a Scottish person might pronounce it "doon." These people have *learned* to move their articulators differently, based on where they learned to speak.

The same person's voice can also be different in different situations. You probably know how different someone's voice sounds when they have a cold. This is because the nose is blocked, changing how air flows around the vocal tract. There are lots of reasons that your voice might change, including who you are speaking to, your mood, and even the time of day. Even if someone said the same thing one hundred times, no two repetitions would be identical. It is important to know about these differences when we compare voices from various situations.

COMPARING VOICES

Due to the biological and behavioral differences in how people speak, voices contain information that is specific to each person. This allows people to be recognized from their voices.

To compare two voices and judge whether they belong to the same person, we need to consider how *similar* the voices are. If they are not very similar, this might suggest that the suspect is not the criminal. We also need to consider how distinctive the voice is. Two people may have similar voices just because they grew up in similar places. Therefore, forensic analysts explore whether the voices contain distinctive features that would not be shared by many people from a similar background. Voices that share a greater number of distinctive features provide stronger evidence that the suspect and the criminal are the same person, because fewer other people's voices would share those features.

It is difficult to say with 100% certainty that a voice in a recording belongs to a suspect because the human voice is so complex. Whereas, our DNA or fingerprints remain fixed throughout our lives, voices change for all sorts of reasons. This means that the same person could sound very different in two recordings made in different situations. In our example, the recording of the criminal's voice could be compared with a suspect's police interview recording. The situation of making a threatening telephone call is very different from the situation of being interviewed by the police, so a person's voice is likely to differ between these two settings. It is also possible that a person will change their voice when committing a crime, to disguise their own voice or sound like somebody else. This may make it very difficult to compare voices, but sometimes features can be detected despite the disguise.

LINGUISTIC ANALYSIS

Voices are analyzed by experts trained in **linguistics**, which is the scientific study of language and speech. Linguists examine various linguistic features in the threatening call and compare them with similar features in the police interview [3]. They break the speech down into various parts and analyze each part by carefully listening to specific sounds. This is called **auditory analysis**. They also examine speech using computer software to look at images of speech sounds, called **spectrograms**, such as those in Figure 1. This process is called **acoustic analysis**.

LINGUISTICS

The scientific study of how languages are formed, used, and understood.

AUDITORY ANALYSIS

A form of forensic speech analysis performed by experts, involving careful listening to different parts of voice recordings.

SPECTROGRAM

A visual representation of a sound signal, such as speech, which shows the frequencies that are present and how they change over time.

ACOUSTIC ANALYSIS

A form of forensic speech analysis performed by experts, making use of spectrograms, and other quantifiable measurements to determine the specific frequencies present in different parts of voice recordings.

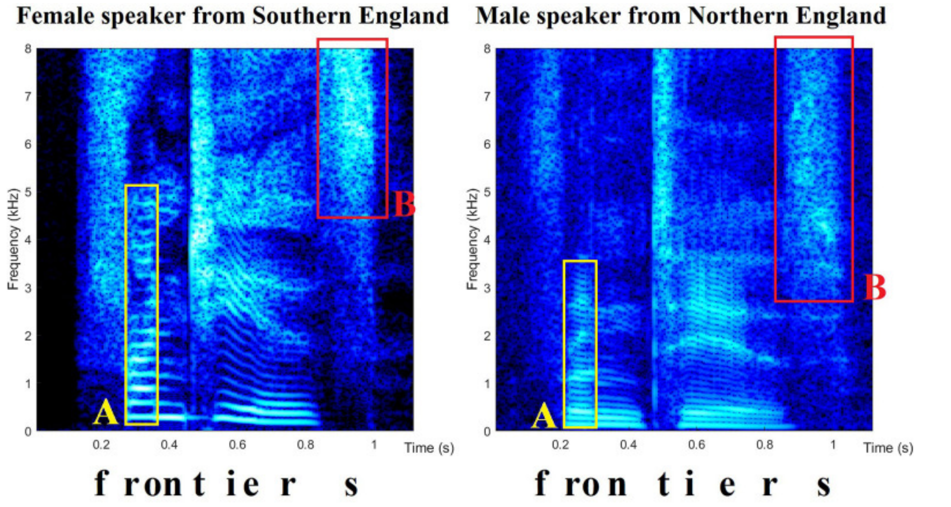

Figure 1

Figure 1

Spectrograms of two speakers saying "frontiers." The brighter the image, the more sound energy there is at that **frequency** and time. There are lots of differences between the speakers: for example, boxes A and B contain the sounds "ro" and "s" but look very different for each speaker. The bright horizontal lines occur whenever the sound has a pitch and are more widely spaced for higher-pitched voices. Noisy sounds like "s" appear as wide **frequency** bands instead of lines and do not have a pitch (try singing "s" and you will find it does not sound different at high or low notes).

Linguistic features that are commonly analyzed include:

Voice quality: The overall sound of someone's voice. Some people's voices sound rough or harsh, some sound creaky or croaky, and some sound like they have a cold. Voice quality is assessed and compared across a range of categories like this.

Pitch: How high- or low-pitched a voice sounds. Pitch changes due to differences in the shape and size of the vocal cords, but also from the way speakers use their vocal cords, for example to express emotion when they speak.

Vowel and consonant sounds: The pronunciation of specific vowels and consonants can be analyzed to show the speaker's behavior, which might help to define the accent a speaker has. There may also be additional unusual features, like a lisp, or producing "r" to sound like "w."

Timing and rhythm: How slow or fast a person speaks, and how they place stress on different syllables and words.

Level of fluency: When speakers pause, hesitate, interrupt, or repeat themselves, these are called **disfluencies**. Some speakers use lots of disfluencies and others use very few; they may also use distinct types of disfluencies.

DISFLUENCIES

Speech habits that interrupt the regular flow of speech, such as pauses, stutters, hesitations, and using filler words like "um" and "er."

Wording and grammar: Speakers might repeatedly use distinctive words or phrases, or they might use unusual sentences in a similar way.

Some linguistic features will be related to the speaker's accent, and some will be more individual. By analyzing a range of features, a full "profile" of each speaker's voice can be generated and compared with other profiles. The forensic analyst can then produce a conclusion regarding how strong the evidence is that the criminal and the suspect are the same person.

AUTOMATED COMPUTER ANALYSIS

Computers can also be used to compare voices automatically, using a process called **automatic speaker recognition** (**ASR**). This is similar to technology used by banks, in which you can use your voice as a password. Rather than analyzing the linguistic aspects of speech, the computer analyzes the voice recording as a whole, identifying the biological as well as behavioral characteristics of a speaker. The computer software makes thousands or millions of measurements from each voice recording and uses complicated statistical models to turn these measurements into a speaker profile. The software also analyzes the profiles of hundreds of other speakers so it can determine whether the profiles are distinctive or not. So, in our case, a sample of speech from a threatening phone call would be analyzed and compared with the police interview. This type of analysis can be used on its own but, in most cases, it is used alongside linguistic experts [4]. One of the benefits of using a computer is that it can analyze hundreds or even thousands of samples, because it works much faster than a human could.

AUTOMATIC SPEAKER RECOGNITION (ASR)

A form of speech analysis performed by computers and based on a large database of voices, to determine how similar, and distinctive two voice recordings are.

CONCLUSION

There are lots of differences between people's voices, and some differences are biological while others are behavioral. By comparing many voice characteristics, especially those that are known to vary a lot between individuals, experts can decide how likely it is that two voice recordings come from the same person. This type of voice comparison evidence can be provided for the police or for a court. This evidence might help law enforcement decide whether they have the right suspect, or used in a trial to help decide if a person is guilty of a crime. Now that almost everyone has a smartphone that can easily record audio and video, voice evidence is becoming more common and can be critical in solving crimes.

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YOUNG REVIEWERS

RYAN, AGE: 15

I really enjoy coding and I love Rubik's cubes. I also really love playing Minecraft.

WILLOW, AGE: 13

My name is Willow (named after the character from Buffy the vampire slayer), and I am an 8th grader at a local middle school. I love playing soccer and kicking around a ball with my dog, Suki. In my free time, I enjoy baking and hanging out with friends.

AUTHORS

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Dr. Jessica Wormald is a forensic consultant at J P French Associates, an independent forensic speech and acoustics laboratory in York, UK. She acts as an expert witness and works primarily on voice comparison and transcription cases. She has carried out research into new and developing accents in different locations in the UK, using used forensic methods as well as ultrasound and automatic methods. She is also a courtesy associate lecturer in the Department of Language and Linguistic Science at the University of York.

frontiers FOR YOUNG MINDS

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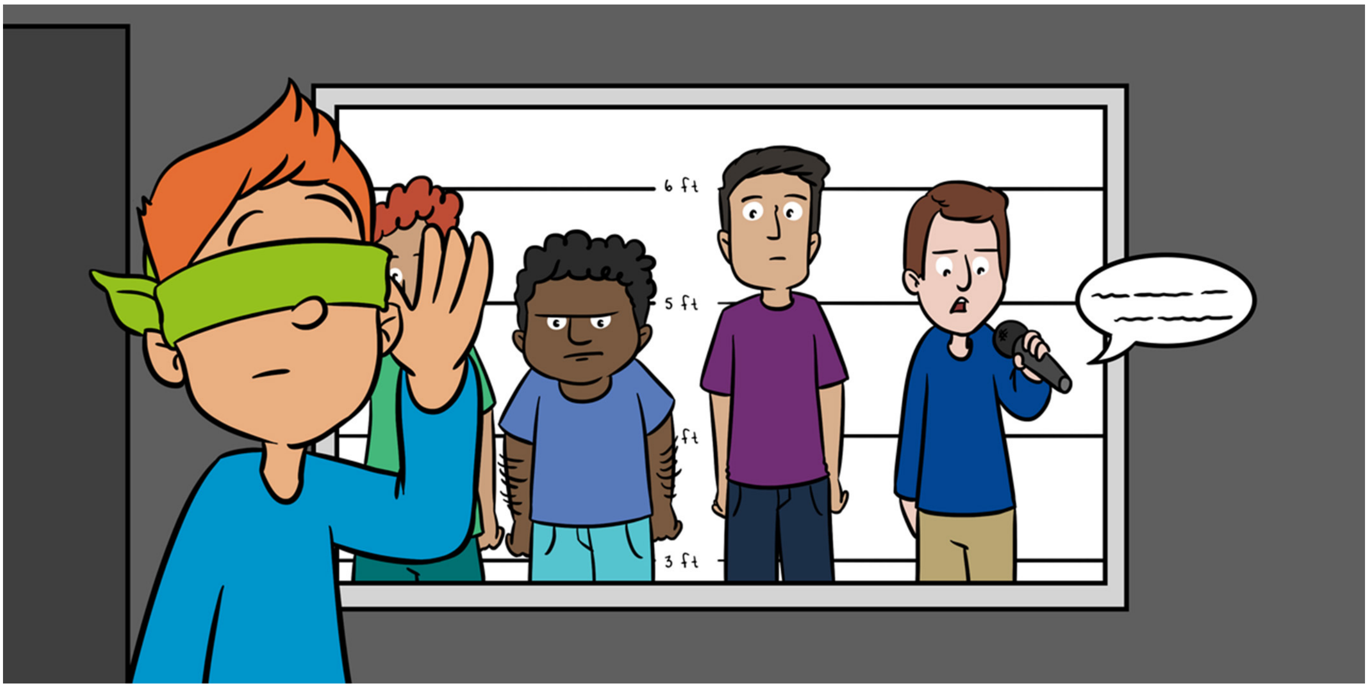

IS IT POSSIBLE TO IDENTIFY A CRIMINAL BY VOICE ALONE?

***Harriet M. J. Smith*[1*], *Nikolas Pautz*[1] *and Katrin Mueller-Johnson*[2]**

[1] *Department of Psychology, Nottingham Trent University, Nottingham, United Kingdom*
[2] *Faculty of Law, University of Oxford, Oxford, United Kingdom*

YOUNG REVIEWER:

ETHAN
AGE: 9

Imagine you overhear someone talking about a robbery they just committed. You hear their voice, but you can not see them. A few weeks later, the police ask you to identify the person you overheard, from a voice lineup. You listen to different peoples' voices and try to pick out the criminal. Do you think you would be able to do it? Perhaps you think you would be able to identify the criminal because you can easily recognize the voices of your family and friends. In fact, recognizing a stranger's voice is difficult. There are many reasons you might struggle to remember a stranger's voice accurately. We will learn about how memory for voices works, and how it can help us predict whether an "earwitness" will correctly select the guilty person. We will also learn how the police can help an earwitnesses to pick the criminal out of the lineup.

EARWITNESS

A person who has overheard, but not seen, something that might help the police solve a crime.

WOULD YOU BE A GOOD EARWITNESS?

An **earwitness** is someone who hears information that is useful to the police. The information an earwitness provides can help to convict criminals. Imagine that you are an earwitness. You are on a train, and you overhear a stranger talking to his friend on the phone. He is talking about a robbery he just committed. You cannot see the stranger's face because he is sitting behind you. However, you can clearly hear his voice. You notice that he speaks with an unusual accent. The phone conversation continues for around 10 min. You report the conversation to the police as soon as you get home.

SUSPECT

Someone who the police think has committed a crime. It is important to remember that the police may or may not be correct.

FOIL

A lineup voice that does **not** belong to the suspect.

Two weeks later, the police tell you that they have arrested a **suspect**. To make sure they have the right person, they ask you to come into the police station and listen to a voice lineup. You listen to recordings of 9 different voices and try to identify the person from the train. You are told that only one of the voice recordings is that of the suspect, and that all of the other voices belong to people who are **foils**. Each voice recording lasts around 1 min. Once you have listened to all 9 voices, you try to identify the person from the train. You find it difficult and you are not very confident in your decision because the voices sound quite similar to each other.

After you have selected someone, the police thank you for your time and you go home. A few weeks later, you find out that the person you selected will be sent to prison for the robbery.

HOW ACCURATE IS VOICE IDENTIFICATION?

Voice identification can be used as evidence in court to help convict criminals. Should we trust voice identification evidence? Well, psychological research has shown that earwitnesses are likely to select the wrong person from a voice lineup [1]. If the police have arrested an innocent person, the wrong person might be sent to prison, and the guilty person would never be punished. There are three reasons why voice identification is difficult. First, when we try to identify a person, we normally depend on the person's face, not their voice. Second, when we listen to someone speaking, we tend to concentrate more on what they are saying, rather than what their voice sounds like. Finally, memory does not work like a video camera. Just because you heard something previously does not mean you will be able to remember it clearly later [2].

ENCODING

The process of creating a memory.

STORAGE

The process of keeping a memory in your mind so that you can later remember it.

RETRIEVAL

The process of thinking about, or talking about, something you remember.

HOW DOES MEMORY WORK?

Psychological researchers often explain memory as having three stages (Figure 1). **Encoding** happens when you create a memory (like when you overhear a person discussing a robbery). **Storage** is the period of time between encoding and when your memory is tested (such as the 2 weeks before you visit the police station). **Retrieval** is when your memory is tested (when you try to identify the person from the train).

Figure 1

The three stages of memory. The arrows show information entering the memory system during encoding, information being stored in the brain, and information leaving storage during retrieval.

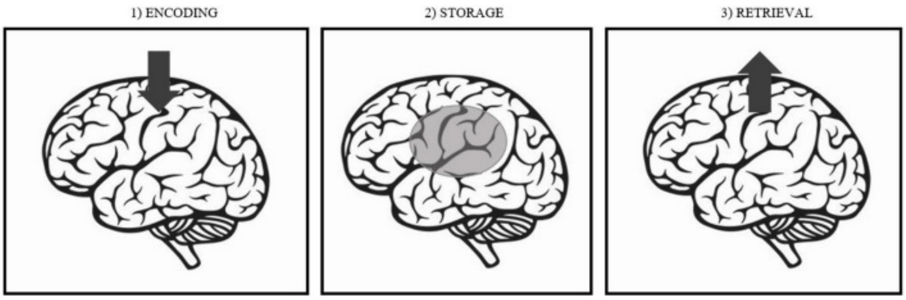

Figure 1

Memories are fragile and can be damaged at any of these three stages. Your memories are not necessarily accurate. Damage to the original memory can occur without you noticing. You may believe you have accurately identified someone from a voice lineup when in fact you have not. Equally, you may feel very unsure about your decision, but your decision might be correct.

Even if your memory for a voice is good, your voice lineup decision might be affected by your expectations. If you believe that the police are likely to have arrested the correct person, this might lead you to select one of the voices as the suspect. If you feel the police have arrested the wrong person, you might decide not to select anyone.

Based on the complex stages of memory, we know that earwitnesses are likely to select the wrong person from a voice lineup. To predict whether an earwitness has identified the correct person, we need to learn more about the ways memories can be damaged at the encoding, storage, and retrieval stages.

WHAT INFLUENCES VOICE IDENTIFICATION ACCURACY?

There are many variables that might affect the accuracy of voice identification. In earwitness research, these variables can be divided into two main categories: **estimator variables** and **system variables** [3].

ESTIMATOR VARIABLE

Something that might affect a witness' memory, but that **cannot** be controlled by the police.

SYSTEM VARIABLE

Something that might affect a witness' memory, that **can** be controlled by the police.

Estimator Variables

Estimator variables can damage memories at the encoding and storage stages. They are associated with the characteristics of the witness, the suspect, and the environment in which the event took place. Estimator variables have their name because the police were not at the crime, so they can only *estimate* the effect of these variables on memory. Understanding which estimator variables are relevant in a crime helps us to predict whether an earwitness is likely to be accurate.

However, once estimator variables have damaged a memory, there is nothing that can be done to undo the damage.

Several estimator variables may have been present during the conversation you overheard on the train. One is familiarity, which is how familiar you are with a person's voice. If you are familiar with a person's voice, you will probably be able to accurately identify that person in a voice lineup. If the voice belongs to someone you have never met, it might be more difficult [4]. On the train, you overheard a stranger's voice, so the voice lineup would have been particularly difficult.

Duration is another estimator variable. The amount of time that you spend listening to someone speaking can affect how difficult it is to pick their voice out of a lineup [5]. If you listen to a voice for a long time, you hear a greater variety of words and sounds. This means it might be easier to match these words and sounds to the suspect's voice in the voice lineup. On the train, you heard the stranger talking for around 10 min. This would make the voice lineup easier than if you had only heard the person saying a few sentences.

The last estimator variable is distinctiveness. Everyone's voice sounds different, but some voices are particularly distinctive, which means that they stand out from other voices. You are more likely to be able to identify a distinctive voice than an average-sounding voice [6]. The stranger on the train had an unusual accent. This may make the voice lineup easier for you.

System Variables

System variables relate to how the voice lineup is conducted. If the lineup is conducted badly, system variables can damage memory at the retrieval stage. On the other hand, system variables can be controlled by good police work to minimize the damage to memory.

Lineup procedure is one system variable. There are various ways of asking someone to respond to a voice lineup, which may affect that person's ability to identify the suspect. When you visited the police station, you listened to all 9 voices before making a decision. However, the police could have played one voice at a time and asked if you recognized the person or not. Researchers are currently investigating which type of procedure is best for voice identification.

Another system variable is called lineup composition. When choosing voices to be part of a voice lineup, it is important that the foil voices sound like the suspect's voice. This keeps the lineup fair because the suspect's voice does not stand out too much. However, including similar-sounding voices might make accurate voice identification quite tricky because it is difficult to distinguish between similar voices. This could be why you found the voice lineup at the police station difficult.

The last system variable is recording length. The voices you heard in the voice lineup were each played for 1 min, which is quite a long time. You might imagine that listening to a longer recording would help you to compare each voice to your memory of the stranger's voice. However, our research has found that listening to shorter recordings does not increase the chances of being wrong [1]. In fact, it might even be *good* to include shorter voice samples because listeners do not get tired from paying attention to the voice recordings.

CONCLUSION

Do you think you would be a good earwitness? Based on everything you have now learned, do you think it is likely that you would be able to pick the stranger from the train out of the voice lineup? Think about how estimator variables and system variables could have affected your performance. Remembering a voice and identifying it from a lineup is not an easy task. There are lots of variables that might make voice identification difficult. It is very important that voice lineups are conducted in the best way possible, so that innocent people are not mistakenly identified as criminals.

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YOUNG REVIEWER

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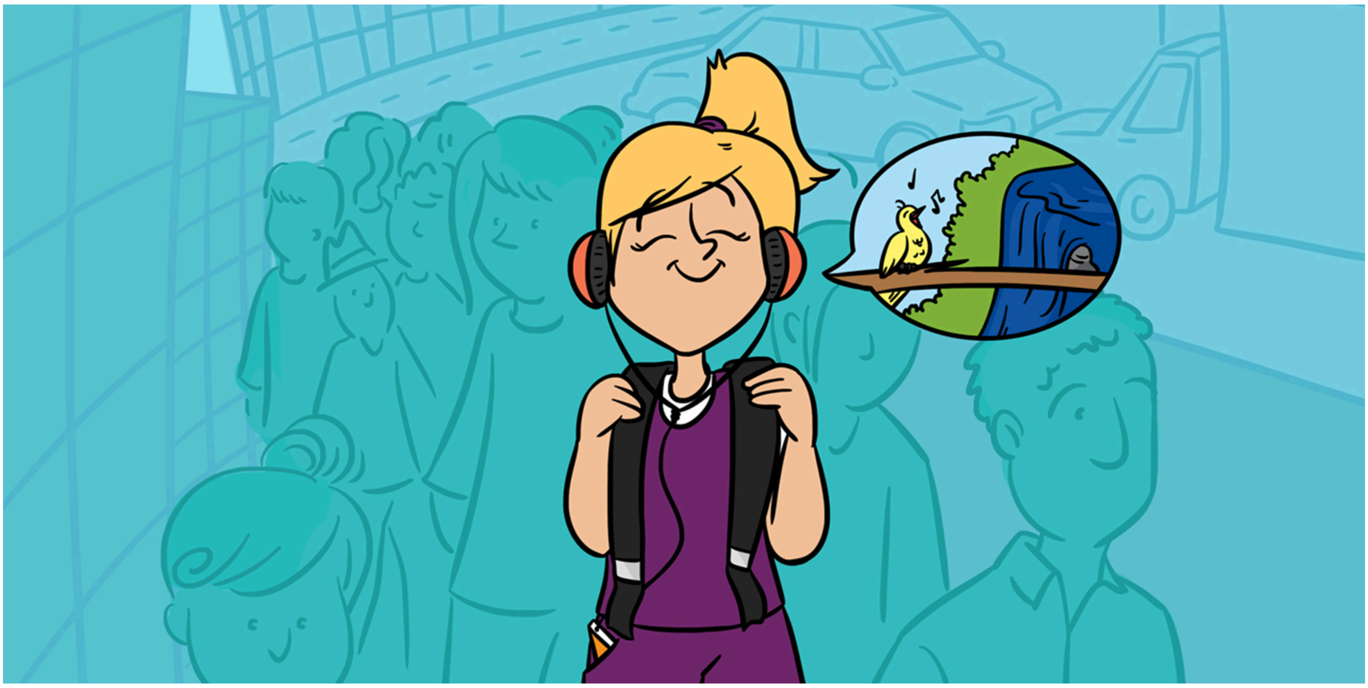

THE SOUNDS AROUND US IN CITIES AND BUILDINGS

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AGE: 13

Sound surrounds us every day, whether we are inside buildings or moving around our cities. But what is "sound" and what is "noise?" What effects can arise from exposure to one or the other? This article will introduce the complex and fascinating world of sound, highlighting the opportunities that acoustic scientists have to reduce noise pollution and to design cities and buildings that sound good to our ears, to improve people's health and wellbeing.

SOUND VS. NOISE

No matter how hard we try, we will never find a place that is completely silent. If something moves, it produces a sound—even if humans cannot hear it. Sounds are everywhere, all around us. The sounds we usually notice are produced by people or by things that people use. Think about road traffic or industries, for instance. Yet, nature can be very loud too! Imagine how noisy an erupting volcano or a tornado might be!

In general, sounds are neither good nor bad. What listeners think of them, though, makes all the difference. If a sound makes us unhappy or annoyed, we think of it as **noise**. The word "noise" comes from the Latin word "nausea," which actually means seasickness. When we listen to a sound that we do not like, it makes us feel uncomfortable, hence "sick." But noise might just be a sound in the wrong place or at the wrong time.

NOISE

A sound that makes one unhappy or annoyed, with the potential for more severe adverse health effects.

In cities, we often talk about noise pollution, which refers to noise levels that make some people unhappy. You might be surprised to learn that noise is not a modern problem. Many cities of the past were also noisy places. Back in the sixth century BCE, the ancient Greek colony of Sybaris was so noisy that the province's council told potters and tinsmiths that they must live outside the city walls because they were so noisy! As human civilizations developed, cities kept growing and became more crowded. Today, most people live in towns and cities and with more people comes more noise! In fact, the World Health Organization (WHO) reported that, in Europe, around one out of every five people are exposed to noise levels that are too high and potentially dangerous for their health.

MEASURING SOUND

When it comes to sounds, how loud is too loud? How noisy does a noise have to be before it is a problem? Noise levels are usually measured in a unit called **decibels** (dB).

DECIBEL

Unit used indicate the intensity or loudness of a sound, with louder sounds corresponding to higher dB levels.

Imagine a person standing a meter away from you, talking in a normal voice. The sound they produce would measure around 60 dB when it enters your ears (Figure 1). Measuring sound can be a very complicated business. This is because the decibel is a logarithmic unit, which means we cannot add or subtract decibel levels as we would with "normal" numbers. For instance, two sound sources emitting 50 dB each will not add together to produce 100 dB of sound, but instead would measure 53 dB!

The WHO has published recommendations on how much noise is acceptable in various places and circumstances. For example, imagine standing outside a house at night, with people sleeping inside. You are measuring the sounds around you with a microphone and a noise level meter. The WHO would say that road traffic noise should not be louder than 45 dB, railway noise should be no higher than 44 dB, and aircraft noise must be below 40 dB [1]. These limits are different because some noises are more annoying than others!

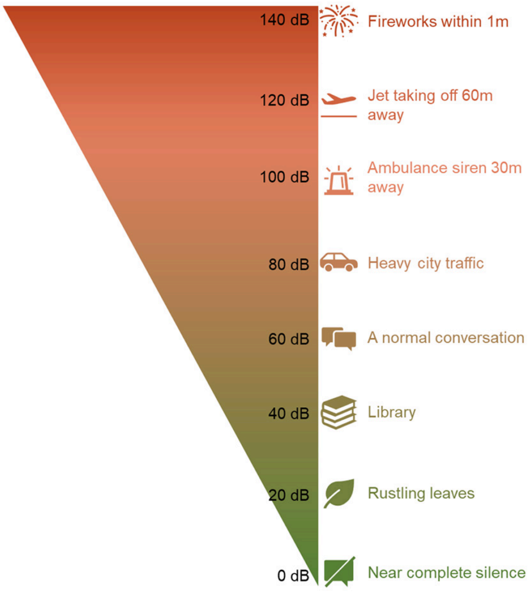

Figure 1

Sound level values for certain sound sources.

SOUNDS CAN ENRICH OUR LIVES

Most people would agree that a totally silent world might not be a pleasant one. Many sounds enrich our lives and make our everyday experiences interesting and meaningful. So, it is important that we do not always look at noise as a bad thing, or as a "pollutant"—some sounds can be positive [2]. For example, listening to natural sounds such as birdsong or running water can help reduce stress and improve wellbeing and mood [3, 4]. Try listening to the sound from London's Regent's Park in Video 1. How does it make you feel? Similarly, hearing music in public spaces can help people feel happier, more excited, and more connected to others. Try listening to the vibrant sounds of London's Covent Garden in Video 2. How do these sounds make you feel?

VIDEO 1

Sounds from London's Regent's Park. The recordings were sourced from the International Soundscape Database.

VIDEO 2

Sounds from London's Covent Garden. The recordings were sourced from the International Soundscape Database.

Some sounds may be so unique that they become a "soundprint" of a place. When we hear these sounds, we instantly know a lot about the location, without needing to be there or even see it. For example, many people would recognize the sound of a cheering football crowd and know it was coming from a football stadium during a match. Can you think of any other easily identifiable soundprints?

MANAGING INDOOR SOUNDS

So far, we have talked about cities and outdoor spaces. But many of us spend a lot of time *inside* buildings. We hear sounds from both *inside* and *outside* the rooms we are in. For example, if you are sitting on the sofa, you might hear laughter from the television, the footsteps of someone walking around upstairs, the rustle of the wind in the tree outside the window, or the sound of a siren from the street beyond.

When we are inside, the sounds we hear travel through the air and may also travel through the walls of buildings, the glass of windows, or the materials that make up the ceiling. When sound hits a wall, part of the sound is reflected, part is absorbed by the wall, and the rest passes through the wall. Some surfaces are good at soaking up sound, while others work more like mirrors, reflecting sound.

If you have ever been inside a church or a large, empty school hall, you will know that the sound of your footsteps can seem very loud. This is because the sound your feet produce is reflected over and over again by the hard stone walls and floors. These reflected sounds reach your ears at slightly different times, depending on how far each reflection has traveled. The result is that you hear an echo that seems to bounce around the room. Sometimes these sound-reflecting surfaces are specifically shaped and positioned to direct the sound, for instance toward the listeners in a concert hall.

In contrast, soft, porous surfaces absorb most of the sound that hits them. The sound squeezes into the air-filled cavities of such surfaces, losing part of its energy in the process. You can find such **sound-absorbing** materials in cinemas, for example—soft seats, padded walls, and heavy curtains. These soft materials prevent echoes, making it much easier to understand and enjoy the movie. Other sound-absorbing materials include thin panels that vibrate when hit by sound waves, to weaken the reflected sound.

SOUND ABSORPTION

Phenomenon relating to the reduction of reflected sound when it hits a surface.

But what if we want to minimize the amount of sound traveling from one indoor space to another? One way is to look at "**sound insulation.**" Walls can provide good sound insulation, although some walls are better at reducing sounds than others! If you live in an apartment and can you hear your neighbors talking, singing, sneezing, or shouting, the walls might not provide very good sound insulation! Good sound insulators include materials that are rigid and heavy, with a continuous non-porous surface. An excellent strategy for creating a sound-insulating wall is to make it like a sandwich: the outer "bread slices" are made of rigid materials, while the inner "filling" is made of soft, sound-absorbing material.

SOUND INSULATION

Phenomenon relating to the reduction of sound transmitted through a wall or ceiling when it hits a surface.

When sounds and noises finally reach our ears, they are conveyed down our ear canals and picked up by special sensors inside our inner ears. These signals then travel to our brains, which process and interpret them in complicated and fascinating ways. Some sounds will capture our attention, while others will go unnoticed. Some sounds are so loud that they cover up quieter noises. This is called **acoustic masking**, and some places use acoustic masking to make noisy environments more comfortable. Have you ever been in a large, busy shop or cafe? These places are full of sounds: people talking, pots

ACOUSTIC MASKING

Phenomenon that occurs when the perception of one sound is affected by the presence of other sounds.

clanking, trollies being pushed around, tills pinging, and items being stacked on shelves. Many shops play music to mask these unpleasant sounds, to make your shopping experience more enjoyable.

AURAL DIVERSITY—EVERYONE IS DIFFERENT

When we are inside buildings, what is "sound" and what is "noise" depends on what we are doing at the time. The sound of voices might be pleasant while you are eating dinner or chilling at home, but annoying if you are at school trying to listen to your teacher. You might like peace and quiet while you are reading a good book, but if you are hanging out with friends, you might prefer to have loud music playing. Some of us prefer to study in silence, while others find it easier to concentrate with music or the television playing in the background. Some people prefer the quiet of the countryside, while others like the busy hubbub of a vibrant city. We call these differences **aural diversity**, which means that everyone experiences sounds in unique ways [5].

AURAL DIVERSITY

Difference in hearing between individuals.

However, there are some sounds that almost everyone likes. Many of these are natural sounds, like bird song or the sound of running water. Architects and engineers who design or modify buildings and outdoor spaces should think about the sorts of sounds people will hear in those spaces and how those sounds will be affected by the structures they are building. Because of aural diversity, there is no perfect "recipe" for everyone.

CONCLUSION

Environmental sounds are very complex, and while we might be tempted to think all noise is bad, the right noises and sounds can actually make our cities and buildings better places to be. **Acoustic scientists** help to measure sounds and determine which sounds are beneficial and which are harmful to our health. Architects and engineers can use these findings to design spaces that are pleasant and healthy. The right combinations of sounds or **soundscapes** [6], can help people to stay physically and mentally healthy, and even to thrive [7]. Measuring the loudness of sound is only one part of the story—we must also consider the types of sounds around us, how each type of sound moves about, and how all these sounds affect our thoughts, feelings, and emotions. The more we learn about sound and how important it is in our lives, the more likely we are to truly enjoy a world of sound.

ACOUSTIC SCIENTIST

A scientist who deals with the measurement and management of sound and its effects on humans, animals, and ecosystems.

SOUNDSCAPE

The sound environment that individual people perceive.

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YOUNG REVIEWER

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ACOUSTICS OF CLASSROOMS

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YOUNG REVIEWERS
SAINT BERNARD'S CATHOLIC HIGH SCHOOL
AGES: 11–13

In this article we will study sound—specifically, how sound allows us to communicate in a classroom and how we can improve that communication. You will learn how sound is measured and how people called acoustics engineers help architects and designers to make sure classrooms are not too noisy—or too quiet. We even have some experiments that you can do to measure sounds at home, at school, or in a football stadium.

THE SCIENCE OF SOUND

ACOUSTICS
The scientific study of sound and vibration.

Acoustics, the science of sound, is a science that you might not have heard much, if anything, about. Why do people know so little about the science of sound? Perhaps it is because many of us take sound and hearing for granted. Yet, imagine life without your sense of hearing! No music, no laughter, no talking, no singing? When you think of how much we rely on sound, it is surprising that so many people have never heard of acoustics! Of course, some people do not have the ability to hear. In the past 30 years, acoustic engineers have helped a million people across the world overcome hearing challenges using bionic implants, and they have helped hundreds of millions of people through hearing aids. One place acoustics has an especially big effect is in the classroom—you can not learn if cannot communicate!

CLEAR COMMUNICATION

What is a classroom for? Well, it is a space where people can learn by listening to a teacher and talking with other students. Classrooms are spaces where we communicate with others to help increase our knowledge and understanding of the world around us. However, creating a space where communication is easy is not actually as simple as it might seem. Students in a classroom need to be able to hear the teacher talking without being distracted by other sounds such as their friends chatting, the sound of a passing truck or a football match being played outside [1–3].

We call the sound a person wants to hear the **signal**. In our example, the signal is the teacher talking [4]. We call all the other sounds **noise**. Noise includes the distracting sounds the person does not want to hear. For a classroom to work well, students need to hear more of the signal and less of the noise. We call this the **signal-to-noise ratio**, and this is where acoustical engineering comes in! Acoustic engineers can help design classrooms to reduce the amount of distracting noise coming from outside and to help manage noise created by students inside. Acoustic engineers are often hired to improve the way schools are built and make sure they are made of the best materials, to ensure communication is as clear as possible. Acoustic engineers also provide guidance for builders and architects. The work of acoustic engineers helps create a comfortable place to learn, where students hear what their teachers are saying[1].

SIGNAL

A wanted sound that carries information.

NOISE

Unwanted sound.

SIGNAL-TO-NOISE RATIO

A comparison of the wanted sound level to that of the unwanted level. A positive result is helpful to communication of information.

[1] You can find more information on the standard guidance for designers here: https://www.gov.uk/government/publications/bb93-acoustic-design-of-schools-performance-standards.

ACOUSTICS

Sound is measured in a unit called **decibels** (dB). Sound involves unusual maths because it is measured on a logarithmic scale. We can use another logarithmic scale, the Richter scale, as an example. The Richter scale is used to measure earthquakes and runs from 0 to 10, while decibels run in a scale from 0 to 100. A magnitude 5 earthquake will shake your home and perhaps knock a garden wall down. A magnitude 6 earthquake is not just a little stronger—it is 10 times stronger than a magnitude 5! A magnitude 6 earthquake will destroy a house, a 7 (10 times stronger than a six) will destroy a town, an 8 will destroy a city, a 9 will destroy a small country and a 10 will destroy a large country. The largest earthquake ever measured was 9.2 on the Richter scale!

DECIBELS

The unit of measurement of sound, typically 0–100 dB.

Now back to acoustics. The dB scale works the same way, except that it runs from 1 to 100. The "dec" part of "decibel" means 10, which is the fold increase between numbers on a logarithmic scale. The quietest sound you can hear is 0 dB, and you can only hear this in a special room called an **anechoic chamber**, which means a room without echo—a very strange room (Figure 1)[2]. The sound of someone whispering is around 20 dB. 40 dB would be someone talking quietly, and if you were chatting to a friend, your voice would probably measure 60 dB. When a teacher is talking to a whole class, the teacher's voice probably measures 70 dB, but if the teacher is shouting, their voice would be around 80 dB.

ANECHOIC CHAMBER

A room without echo achieved by covering every surface with sound absorbing material such as foam.

[2] View a video here: https://www.youtube.com/watch?v=LQsz7SzmU8s&t=7s.

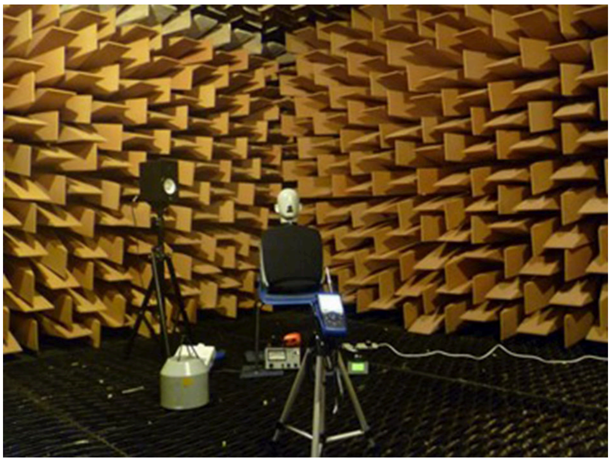

Figure 1

Figure 1

An anechoic chamber a special room that does not have echoes. Note the thousands of sound-absorbing foam wedges.

CLASSROOM ACOUSTICS

Not only can we measure how loud a sound is, we can also measure how echoey a room might be. This is measured in seconds and called **reverberation time** (RT). RT is defined as the length of time it takes a sound to completely disappear. For example, if you sneeze, how long is it before the whole sound of that sneeze has gone? This depends on whether you sneeze at a swimming pool or in the gym. An anechoic chamber has a reverberation time of 0 s. Here is a simple experiment you can try at home or school to illustrate this point. You will need a balloon and a sharp pencil since sneezing is not very reliable signal!

REVERBERATION TIME

The length of time (in seconds) that a sound takes to be stopped being heard. The sound is usually created by an impulsive sound (balloon burst).

First blow up the balloon and tie a knot in the end so it stays inflated. Next, make sure everyone in the room is completely silent. Now pop the balloon using the pencil. BANG! As you do so, start counting or use a timer. In a normal classroom, the sound should take about 1 s to disappear. Now repeat the experiment in your school hallway, an echoey corridor, or the gym. You will probably discover that the sound takes longer to disappear in bigger spaces, especially spaces with fewer carpets, curtains, or furniture.

So, RT is different depending on where you are. Acoustic engineers aim for the RT in modern classrooms to be around 0.8 s (Figure 2). This means that any sounds will disappear after 0.8 s. Classrooms in old buildings with high ceilings might have a higher RT because they are more echoey (Figure 3). It can be much harder to hear what the teacher is saying in these kinds of spaces.

Figure 2

Figure 2

A modern classroom, where reverberation time is usually around 0.8 s.

Figure 3

Figure 3

A Victorian classroom, where reverberation time is around 1.5 s. It was harder to hear the teacher back then!

Where the RT of a room is too high and sound is echoing around and making a lot of noise, adding soft materials such as cushions, carpets, and curtains can help absorb, or soak up, the sound. Acoustic engineers use a number called an **absorption coefficient** to describe how well materials soak up sound. A rock has an absorption coefficient of 0, and something that completely absorbs all sound has an absorption coefficient of 1. An open window also has an absorption

ABSORPTION COEFFICIENT

A material characteristic describing the amount of sound that is absorbed. Ranges from 0 for hard materials (marble) to 1 for soft material (foam).

coefficient of 1, because the sound goes out the window and does not come back. Glass has an absorption coefficient of 0.03, and wood is around 0.1.Cushions have an absorption coefficient of 0.9[3].

[3] For more information, see: https://www.engineeringtoolbox.com/accoustic-sound-absorption-d_68.html.

With the correct information, we can work out the RT of any room, We do this using the following equation:

$$RT = \frac{0.16 * V}{S\alpha}$$

V is the size of the room (volume) in cubic meters (m^3). *S* is the walls, ceiling, and floor combined, measured in square meters (m^2) and α is the absorption coefficient of whatever the room is made from.

Imagine a greenhouse made entirely from glass that is 2 m long, 2 m wide and 2 m high. The size or volume of the greenhouse is $2 \times 2 \times 2 = 8\ m^3$. Each wall, floor and ceiling would each have an area of $2 \times 2\,m = 4\ m^2$. There are four walls plus one floor and one ceiling). So $S = 6 \times 4 = 24\ m^2$. We know the absorption coefficient of glass is 0.03. The equation becomes:

$$RT = 0.16{\times}8/24{\times}0.03 = 1.78s.$$

In other words, inside our small room made entirely of glass, any loud sound made would last for 1.78 s.

In the real world, however, most rooms or indoor spaces are made up of lots of different materials—the brick of the walls, the glass of the windows, curtains, carpets, furniture, and even people. So, calculating the RT of real spaces can be a bit trickier!

WHEN ACOUSTICS MADE A BIG DIFFERENCE

Acoustics are not just important in classrooms. They affect all sorts of things in our world, including sport. In the semi-finals of the UEFA Champions League, in 2011, when Arsenal was playing Barcelona, the referee blew his whistle to draw the attention of the players. Robin Van Persie ignored the referee and kicked the ball at the goal, after which he was sent off. In an interview after the match, he said he had not heard the whistle and could not be expected to hear such a sound above the noise of 90,000 shouting fans. Perhaps if the stadium had had better acoustics, the player would have heard the referee and not been sent off?[4].

How loud *is* a crowd of 90,000 people? Here is an experiment you can do to find out!

First, you or a teacher will need to download a sound-measuring application onto a smartphone[5].

[4] You can watch a video of this moment here: https://www.youtube.com/watch?v=pu537wHKyGc.

[5] Check out these apps: www.studiosixdigital.com Smartphone App. 2021. www.Faberacoustical.com Smartphone App 2021. https://apps.apple.com/us/app/splnfft-noise-meter/id355396114. https://apps.apple.com/gb/app/decibel-x-db-sound-level-meter/id448155923.

Then you will need 100 students to gather in your school hall, with the person with the phone at the front.

To start, with the app running, one person in the middle of the hall stands up and shouts "Hello!." Everyone else should be quiet. The app will record how loud the sound is in dB.

Next, 10 classmates in the center of the hall stand up and all shout "Hello!" at the same time. Everyone else should be quiet. Record the result from the smartphone.

Finally, all 100 classmates stand up and all shout, "Hello" at the same time. Record the results from the smartphone.

As you increase the number of people shouting, you should see the sound level increase. One person shouting should be around 80 dB,10 people around 90 dB and 100 people around 100 dB. Now imagine increasing this amount of shouting by 10 times again, again and again! That is how loud 100,000 football fans would be!

Is it any wonder that footballers sometimes find it hard to hear the referee? Perhaps if the stadium had been empty and everyone was watching from home, the whistle-blowing might have been a bit clearer!

FINAL THOUGHTS

How noisy is your classroom? Is it easy to hear your teacher or are you distracted by the sound of other things going on in the room? Now that you understand more about how the science of acoustics works, you might have some helpful suggestions that could help reduce classroom noise and make it easier to concentrate! But be careful—if you bring in too many cushions, you might get just a little bit *too* comfortable![6]

[6] If you would like to discover more about what is happening in the world of acoustics look at these sites: www.acoustics.ac.uk. lsbu-acoustics.blogspot.com.

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YOUNG REVIEWERS

SAINT BERNARD'S CATHOLIC HIGH SCHOOL, AGES: 11–13

Saint Bernard's Catholic High School is a Catholic Secondary in South Yorkshire. These KS3 students volunteered to be part of the peer review group. They read the article and made detailed notes in their own time. They loved having an active role in real peer review of this Science article—not just hearing about the process but being actively involved. Having adult authors not just listen but respond too was very empowering for them. Students involved: Sarah, Grace, Alice, Zara, Amelia, Alicja, Emilja, Megan, Edna, and Kate.

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frontiers FOR YOUNG MINDS

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ARE NOISY HOSPITALS MAKING US SICK?

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YOUNG REVIEWERS

74TH NOTTINGHAM GUIDES

AGES: 9–14

If you have ever been woken up by noise in the night, you will know just how annoying it can be. But noise does not only disturb us; it can actually be bad for our health. People can be affected by noise in many environments and, unfortunately, hospitals that are occupied by the most vulnerable groups of people are no exception. Studies show that people trying to recover need peace and quiet. But despite all the “quiet please” signs, noise in hospitals is one of the main reason patients cannot sleep, besides physical pain. In this article, we explore how noise affects people and how it impacts those trying to get well in hospitals.

WHAT IS SOUND AND HOW DO HUMANS DETECT IT?

Things around us produce sound when they are either moving or shaking. We call this shaking movement **vibration** [1]. Think of the strings of a violin, or a car passing by. Even your voice is the result of movements and vibrations. This movement is the reason that sound is also a form of energy, similar to electricity or heat, for example.

VIBRATION

A periodic motion back and forth or from side to side.

Figure 1

Structure of the human ear. Structure of the human ear. The outer ear is the part you can see on the outside of your head—it ends at the tympanic membrane (eardrum). The middle ear consists of small bones called ossicles that transfer vibrations at the eardrum to the cochlea. The cochlea is the main part of the inner ear and it converts vibrations to nerve firings that our brain understands as sound.

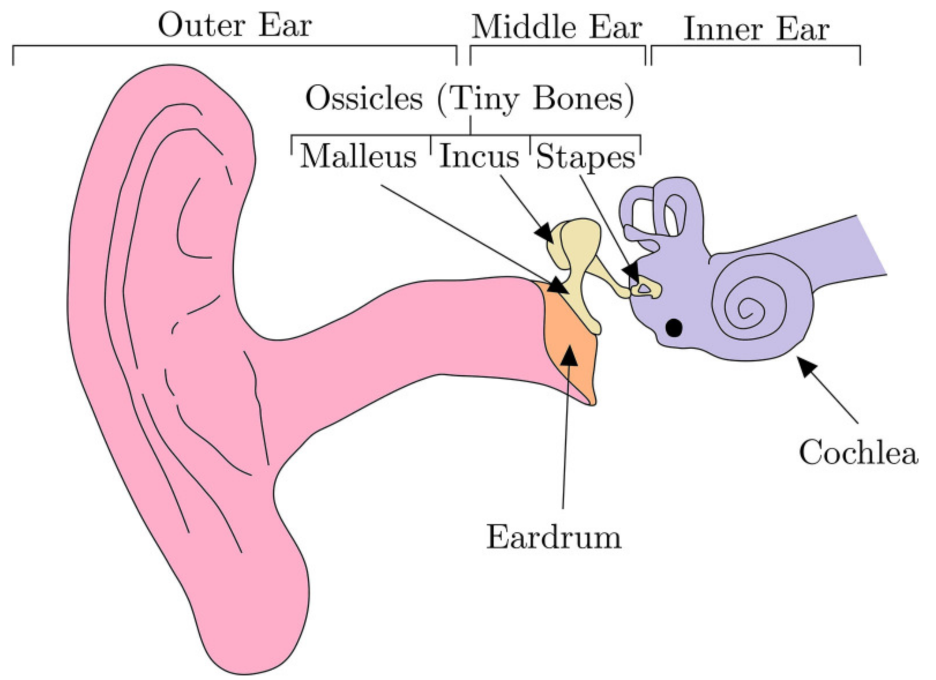

Figure 1

The human ear is made up of three different parts, the outer ear, the middle ear, and the inner ear (Figure 1). When something vibrates, air molecules travel through the air as sound waves. Sound waves are detected by our ears, which convert the waves into electrical pulses that travel to our brains. Sound arriving at the outer ear causes vibration of a small piece of skin-like tissue called the tympanic membrane (also known as the eardrum). The tympanic membrane is connected to a set of three small bones, the ossicles, that make up the middle ear. These bones allow vibrations in the eardrum to act on a tiny organ in the inner ear called the cochlea. The changing pressure in the cochlea caused by these vibrations is then sent to the brain in the form of nerve signals.

PITCH

Allows to judge sounds as "high" and "low."

INTENSITY

The energy carried in sound waves.

Our brains figure out what these nerve signals mean. We can distinguish between the various parts of a sound, such as the **pitch** (how high or low the sound is) and the **intensity** (how loud or quiet the sound is). We are most likely to notice sounds that change in intensity and pitch. A siren is a good example of a sound that has been designed with this in mind, to get our attention.

WHEN DOES SOUND TURN INTO NOISE?

The simplest definition of noise is any sound that we do not want to hear, often sounds we find annoying or disturbing. This definition makes it immediately clear that noise is a somewhat individual judgment, and one that depends on context. For example, your favorite music might sound lovely to you, but might feel like noise to someone else. Even if the other person normally likes the same bands as you, they might perceive your music as noise if you play it very loudly late at night when they are trying to sleep!

Scientists divide noise into three main groups, or categories. These categories make it easier to identify which types of noise affect us the most (Figure 2). **Continuous noise** is the type of noise that occurs without interruption, such as the noise produced by machinery, a fan running non-stop, or a gently crackling fire. As the intensity and pitch of sound remain basically the same, our brains tend to adapt and become less sensitive to continuous noise. As we will discuss later, this type of noise may sometimes be beneficial. **Intermittent noise** often includes fast changes in the noise level, such as an aircraft or a single vehicle driving by in a normally quiet area. This change in noise level tends to trigger the brain and can potentially disturb or even annoy us [2]. **Impulsive noise** is characterized by a sharp and sudden increase in noise level, such as that caused by fireworks or an explosion. Experiments have shown that this type of noise can cause us the greatest annoyance [2].

CONTINUOUS NOISE

Remains constant and stable over a given time period.

INTERMITTENT NOISE

Stops and starts rapidly.

IMPULSIVE NOISE

Rapid and loud noise of short duration 7.

NOISE POLLUTION AND OUR HEALTH

If we do not want to see something, we can close our eyes. But unfortunately, we cannot close our ears! This makes it difficult to protect ourselves from unwanted sounds. People living in large cities are bombarded with noise from road traffic, passing aircraft, sirens, construction, and general human activity. Unwanted sounds like these are often called **noise pollution**. Through many years of research, scientists have learned that long-term exposure to noise can make us unwell. It can increase our stress levels and reduce our ability to concentrate and communicate. Noise disturbance also affects how well we sleep, which can lead to more serious problems such as heart failure or stroke [3].

NOISE POLLUTION

Regular experience of noise levels that can be harmful for humans or other living organisms.

To attempt to address these problems, scientists and engineers have come up with recommended noise targets for different types of buildings, including our homes, hospitals, schools, and workspaces. With the help of these targets, acoustic engineers aim to design buildings that are pleasant to be in. Their acoustic design protects us from too much harmful noise.

Although our buildings are generally designed to protect us from external noise, what about noise that is actually generated indoors? When does this indoor noise become a serious issue?

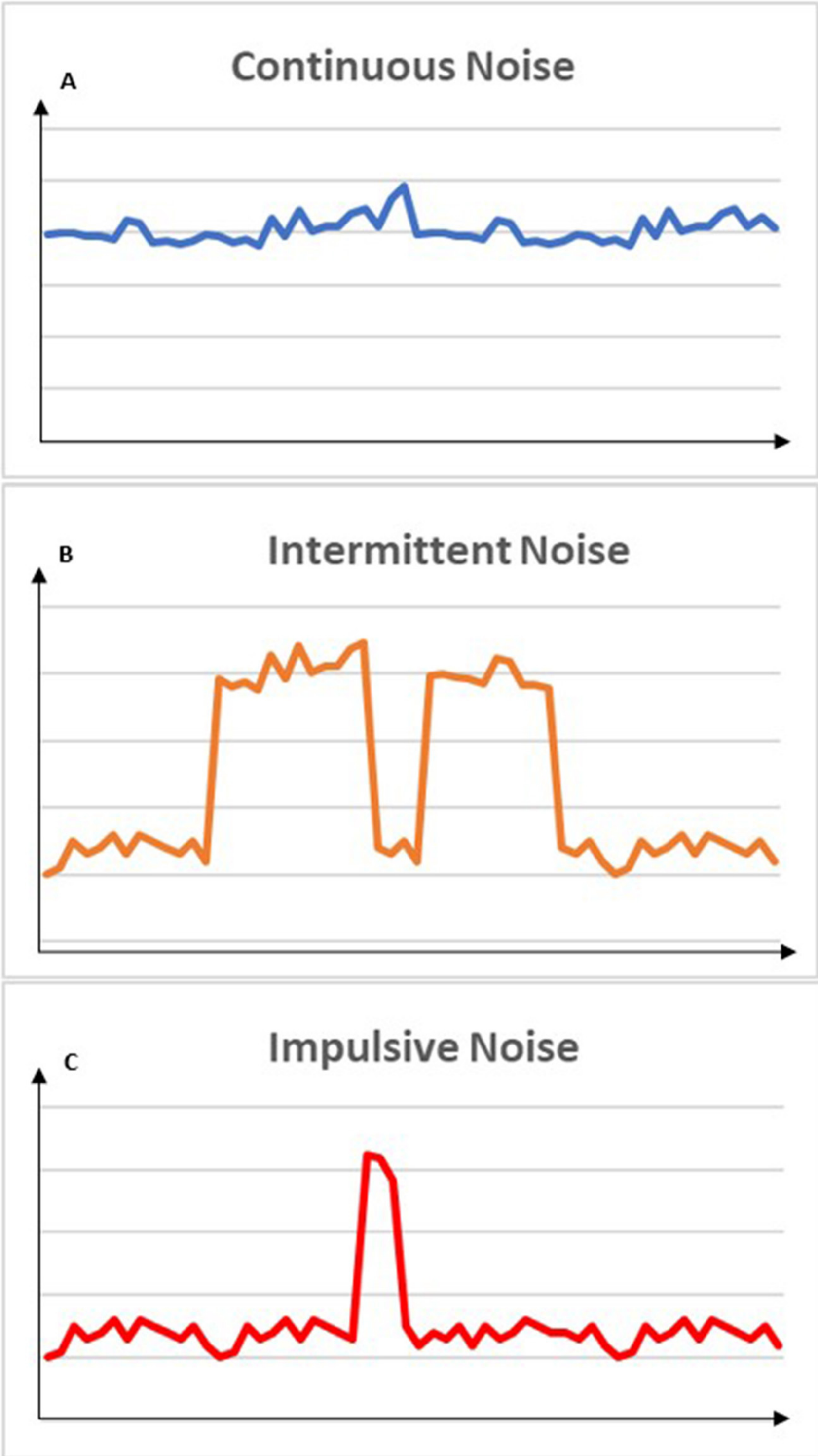

Figure 2

Figure 2

The three main types of noise: **(A)** continuous, **(B)** intermittent, and **(C)** impulsive. Note that each of the plots shows a plot of variation in the noise level over time. This reflects the natural variation in the background noise level that occurs in real life.

NOISE IN HOSPITALS

Hospitals are typically occupied by the most vulnerable groups of people, such as the elderly, sick people, or people with physical disabilities. These groups are often less able to cope with stress than healthy people are. Evidence suggests that people recover better in a peaceful and relaxing atmosphere, so it would be natural to assume that hospital buildings are good at ensuring noise is kept to a minimum [4]. However, sound scientists have discovered that the noise generated from everyday activities in hospitals far exceeds recommended levels. General patient noise, visitor and staff conversations, medical equipment, alarms, televisions, trolleys, phones, and doors all create a highly noisy environment that is difficult to control.

Despite the attempts of many hospitals to reduce noise levels with "quiet please" signs, patients are often exposed to various types of noises at random hours, including at night. In some cases, the noise levels in some hospital rooms are similar to very loud music through headphones and are almost loud enough to damage patients' hearing! As a result of these disruptions, 40% of hospital patients in the United Kingdom have reported that they found it difficult to sleep, which made them feel annoyed and stressed [5]. This means that noise in hospitals can make people who are already sick even sicker, which means they take longer to recover. However, this does not need to be the case. There are methods that can be used to reduce unnecessary noise in hospitals and protect patients' health.

WHAT CAN BE DONE?

Noise can be controlled in three main ways. We can control noise at its source—the place it comes from. Or we can control the noise as it travels—on its path (through the air, for example). Finally, we can control noise where it is received by our ears (Figure 3). Although controlling noise at its source is often considered to be the most desirable, it may not always be possible.

When we think about the problem of noisy hospitals, there are several possible approaches that could be used to protect patients from noise. To control noise at the source level, hospitals could provide training to staff to keep noise low, and they could inform patients and visitors of the importance of being quiet. Hospitals could also avoid unnecessary noise by ensuring hospital equipment, such as trolleys, beds, and doors, is kept in good condition. To control noise at the path level, hospitals could use sound-absorbing panels in patient rooms. They could also use loudspeakers in the ceiling to produce constant background noise, similar to the continuous noise discussed earlier. This type of noise can help patients to be less disturbed by other noise sources. This process is often called **sound masking** [5]. Finally, to control noise at the receiver level, hospitals could give patients earplugs to help minimize disturbance and allow them to sleep further away from noisier areas, such as reception.

SOUND MASKING

Is the generation of certain sounds to cover or partially cover other sounds

Figure 3

Noise can be controlled at three basic levels: at the source of the noise, as the noise travels along its path, and at the level of the receiver—the person who hears the noise.

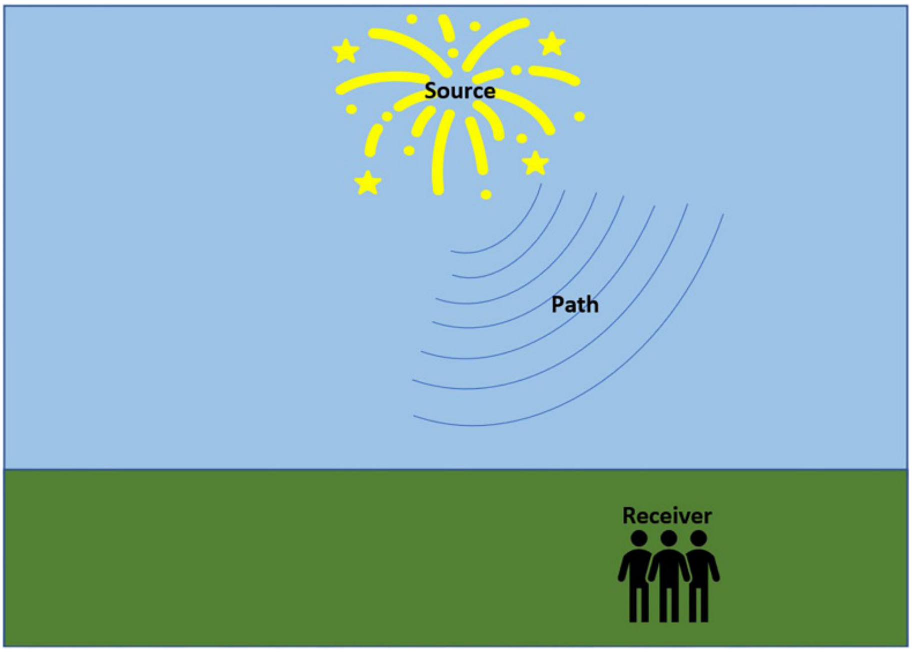

Figure 3

CONCLUSION

Our ability to hear allows us to communicate with one another, to listen to our favorite music, and to protect ourselves from danger. But too much noise pollution is very harmful for our health. Many patients in our hospitals find it hard to sleep because of high noise levels, which can increase the length of time it takes for them to recover. While there are ways to help reduce the impact of noise in our world, there is a lot more to be done to deal with the issue. We hope that, as our world and technology develop, new ways of controlling noise will be invented to help us protect ourselves and others from the harmful effects of noise pollution.

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YOUNG REVIEWERS

74TH NOTTINGHAM GUIDES, AGES: 9–14

Our Guides work together as a unit or as small groups and decide together what to do within meetings. Guides support each other to have fun, make friends, go on adventures and try new things. Guides is a chance to make a difference and they are encouraged to speak out about what matters to them and to do something about it. With this in mind, they were keen to make a difference for anybody staying within a hospital environment.

AUTHORS

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I am a senior acoustic engineer in the Institute of Acoustics (MIOA). I graduated with a bachelor of science in sound engineering, from Southampton Solent University, United Kingdom in 2015. Then I studied at the Institute of Acoustics and received a diploma in noise and vibration control. After graduation, I started working as an engineer in the field of acoustics. Since then, I have been exposed to a broad spectrum of acoustic consultancy and engineering, entailing most sectors in the field, including residential, industrial, healthcare, education, construction, and workspace schemes. *george_hadjilambri@hotmail.com

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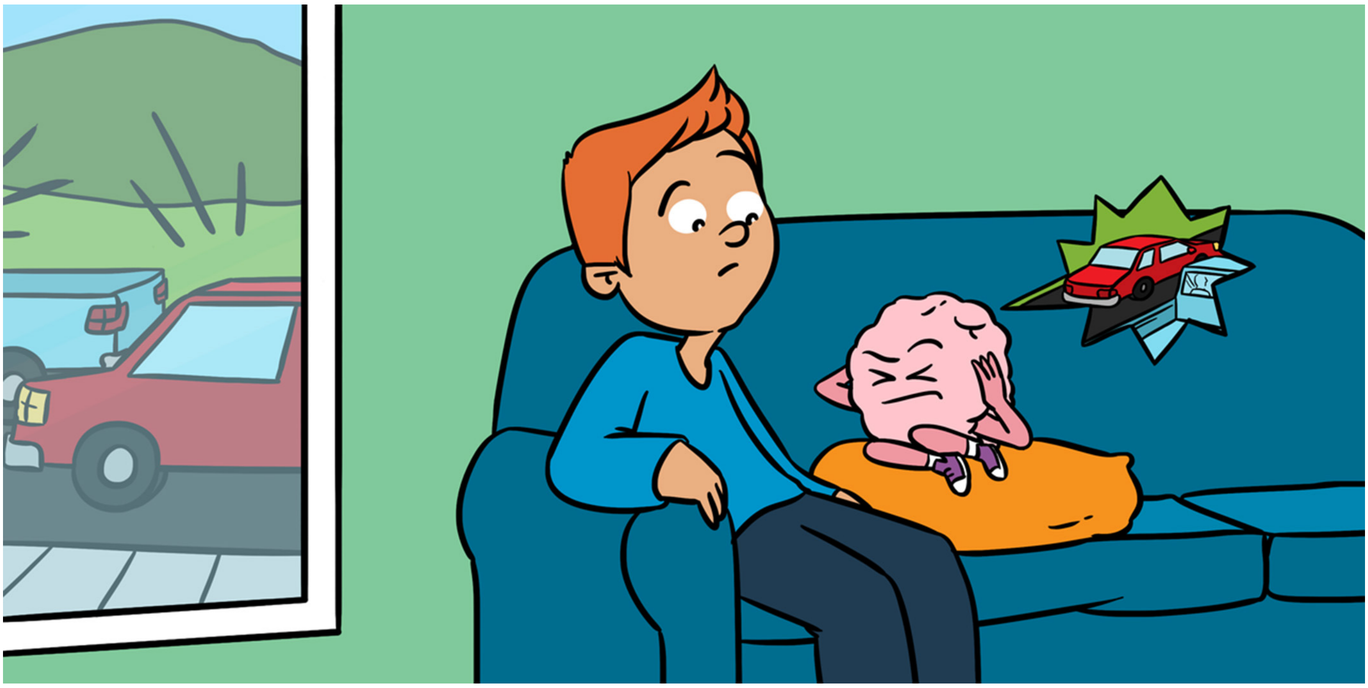

WHAT OUR BODIES TELL US ABOUT NOISE

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University of Salford, Salford, United Kingdom

YOUNG REVIEWERS:

DANIELE
AGE: 16

TOTS & TEENS
AGES: 11–12

Noise is defined as unwanted sound. Not only is noise unwanted, it is expensive and bad for human health. But what sounds like noise to one person might be a happy sound for someone else, so how do we study noise? This article explains how we try to understand and measure noise. We run experiments in a laboratory to measure how noises in the environment affect listeners' thinking, stress levels, and health. We measure the listeners' brain activity, how much they sweat, and their heartbeat changes in response to noises like car engines, train squeals, and airplanes taking off. We match up the brain activity we measure with what people tell us about their responses to noisy sounds. This work will help us to make the world sound better for everyone—the more we understand how we hear, and design better places and spaces to improve our experiences with sound.

PSYCHO-ACOUSTICIAN
A scientist who specializes in understanding psychological reactions to sound.

I am a **psychoacoustician**. That means I am interested in what happens in our bodies and our brains when we hear different kinds of sounds. There are many different kinds of sounds—speech, music, traffic noise, and animal calls, to name a few. This article looks at environmental sounds, which are the kinds of sounds we hear in everyday life across towns, cities, and rural areas. I will describe an experiment in which we play various environmental sounds (trains, planes, car traffic, building noises, and a few others) to people. We want to understand how people feel when they hear these different types of sounds, and ultimately we hope that our work will assist architects, engineers, and planners with their design choices, to make the world sound as good as possible for everyone. But why?

SOUND VS. NOISE

In the modern world, noise is a big problem. But what is the difference between "sound" and "noise"? Essentially, the difference comes down to whether the listener wants to hear the sound. Noise consists of sounds that people do not want to hear. When noise starts to take a toll on human health, it becomes a pollutant. If you have spent any time in a big city, you are likely to have suffered from **noise pollution** at some point. The World Health Organization rated environmental noise as the second biggest health problem facing Western Europe in 2018! Around the same time, the British government estimated that traffic noise—car noise, specifically—cost the economy £8 billion per year, not just from dealing directly with noise complaints but also because noise pollution can distract us from our work or interrupt a good night's sleep, which ultimately brings our productivity down.

NOISE POLLUTION

Unwanted noise, generally in the work or home environment.

Why is noise so damaging? We know that noise affects our sleep and our concentration at school or at work. Noise can make us feel stressed, and there is increasing evidence to suggest that it affects our heart health, too. This makes noise a very serious problem, and a difficult one to deal with. Noise affects all of us differently. One of the biggest challenges for psychoacousticians is understanding human responses
to noise.

PROBLEMS WITH MEASURING NOISE

Acousticians often use technology to measure sound levels. For example, a sound pressure meter might measure how intense the pressure of a sound wave is, but devices like these do not tell us how sounds affect people. We are interested in people's emotional responses to sounds because the **perception** of the sound is what makes it either noisy (annoying and unwanted) or not noisy (wanted). Imagine your friend is enjoying listening to very loud rock music. To your friend, this sound is pleasant and causes good feelings. But if you were in the room next door trying to sleep, you might feel very differently about your friend's music! You would perceive the music

PERCEPTION

A way of measuring the different types of responses we might experience to a given stimulus.

as noise and might find yourself banging on your friend's door to turn it down!

In our experiments, we often try to understand how sounds are pleasant to one person and annoying to another. But how do we measure how annoying a sound might be?

One way to do this is to rate annoyance on a scale of 1–10, with 1 being a very negative emotion and 10 being very positive. This kind of scale is called a **valence**. The trouble is that a very intense and positive emotional response might be excitement, whereas a less intense but equally positive emotional response might be relaxation. A very intense negative emotional response could be anger *or* fear. This illustrates one of the problems with using valence to measure emotional responses—how do we differentiate between two very different emotional responses, like excitement vs. relaxation or anger vs. fear?

VALENCE

A measure of positivity in emotional response.

There is another problem with this type approach: the person being tested must be paying attention. Imagine we are trying to find out how noise affects sleep. We could play loud noises near someone who is sleeping and ask them to tell us how that noise makes them feel. The trouble is, each time we wake the person up, they will become more and more annoyed and find it more and more difficult to get back to sleep. Or perhaps we are trying to work out how noise affects people when they are driving, but asking drivers lots of questions while they are trying to concentrate on the road could be dangerous!

MEASURING LISTENERS' RESPONSE TO NOISE

To overcome some of these problems, we design laboratory tests. We record noises from the real world and play them to people using a technique called **ambisonics**, which is a specialized kind of surround sound. We then measure how listeners' brains and bodies react using **biosensors**, which are devices that record things like heart rate, sweat production, muscle tension, and brain activity.

AMBISONICS

A technique for creating highly realistic spatial audio scenes using multiple loudspeakers.

BIOSENSORS

Sensors which monitor biophysiological reactions, such as heart rate, sweat, or brain activity.

Figure 1 shows a technique called **electroencephalography** (EEG). EEG records brain activity. It works by measuring the electrical activity inside the brain using tiny electrodes in a cap that is placed on the scalp. By watching how these signals change, we can interpret how the brain is reacting to the various sounds that we play for our listeners. We also monitor how much sweat listeners are producing, as this can tell us more about their emotional states, like their levels of tension or relaxation. Finally, we might look at how a listener's heart rate changes over time. Heart-rate variability can tell us more about how the listener is feeling. If you have ever watched a spy movie, you will know that these are the same types of sensors used in lie-detector tests!

ELECTRO-ENCEPHALOGRAPHY

A specific biosensor technique which uses sensors that are connected to the scalp to measure electrical activity from the brain.

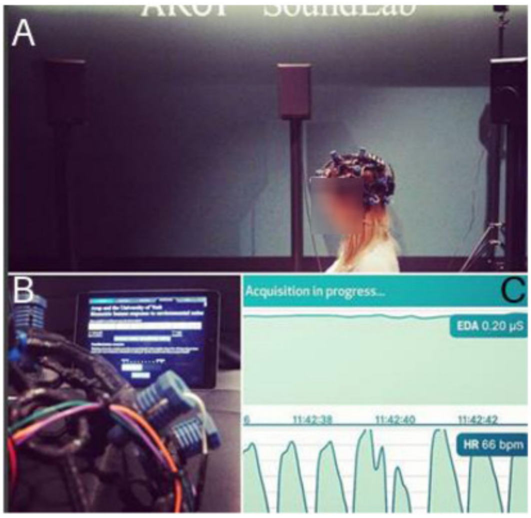

Figure 1

Figure 1

(A) A listener undergoing EEG. She is wearing a cap with electrodes that measure her brain activity, while she is listening to environmental sounds. **(B)** A closeup of the EEG electrodes and cables on the cap. **(C)** A live data stream of electrodermal activity (sweat), and heart rate.

TOPOGRAPH

A graphical representation—in our case, of the surface of the scalp used to show where activity occurs whilst using an electroencephalograph.

EEG is a well-established technology, and there are lots of ways to interpret EEG data by studying the unique patterns of brain activity, which is displayed in the form of a color plot called a **topograph** (Figure 2). EEG can not be used to read humans' minds, but it can help us understand if a person is sad, angry, afraid, or relaxed. EEG topographs give us a much clearer picture of how a person feels than we could get by just asking them, so this technique can help us compare the effects that various sounds have on many individuals.

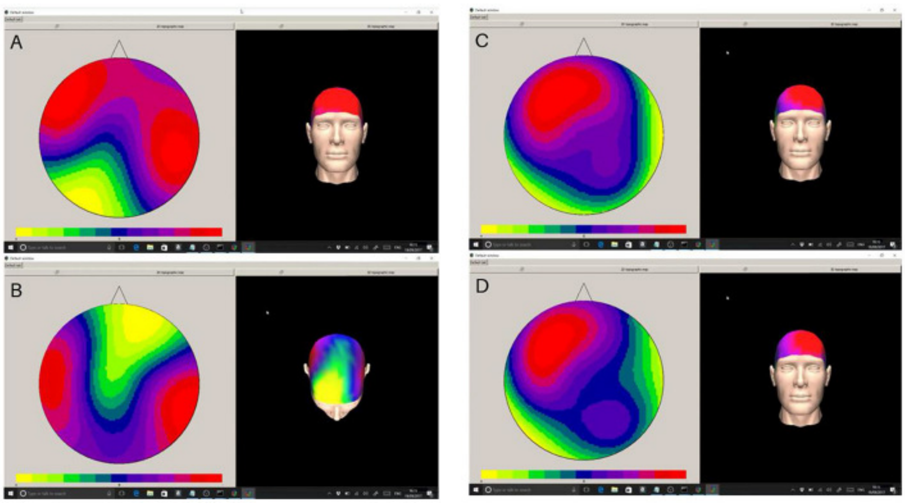

Figure 2

Figure 2

Topographs show electrical activity from the brain, measured on the surface of the scalp. The colors relate to intensity of brain activity. In the scale, yellow is low activity and red is high activity. The triangle at the top of the circle on the topographs on the left represents the listener's nose. If we compare [**(A)**, top pair] "angry" topographs with the topographs of [**(B)**, bottom pair] which are "afraid" topographs, we can see that they are almost exactly opposite to one another. Topographs show electrical activity from the brain, measured on the surface of the scalp. The colors relate to intensity of brain activity. In the scale, yellow is low activity and red is high activity. The triangle at the top of the circle on the topographs on the left represents the listener's nose. If we compare

Figures 2A,B illustrates that an angry topograph is almost the reverse of an afraid topograph. This makes sense, and we even have a common saying about this type of response: *fight or flight*. Anger and fear also have unique and well-known effects on our hormonal responses including the release of substances like endorphins. Measuring these

[(C) top pair] "happy," with the topographs of [(D), bottom pair] which are "sad" topographs, we can see that they are very similar to each other.

hormones and others can further help us to study the effects of noisy sounds on people's bodies.

Something interesting happens when we play people happy vs. sad sounds—the topographs do not show much of a difference (Figures 2C,D)! At first glance that does not make sense—why would people feel the same, whether they are hearing happy or sad music? Well, we know that people enjoy listening to sad music sometimes—maybe you can think of a few sad songs that you like! This taught us that we should think about these responses as indicating *enjoyment*. We also have a saying for this type of response: "I did not know whether to laugh or cry!"

WHAT ABOUT ENVIRONMENTAL SOUNDS?

When we asked people to rate their own level of annoyance to environmental sounds, we obtained some interesting results (Figure 3). According to our listeners, the construction noise was the most annoying sound. And the least annoying sound? Interestingly, it was the traffic sounds! But most of our listeners lived in a major city, so perhaps they found those sounds quite normal.

Sample	Average rating	st.deviation
Breaker	7.3	2.1
Tram squeal	7.2	2.0
Aircraft	6.9	2.0
Aircraft	6.6	2.0
High speed train	6.4	2.0
Highway	5.2	2.4
Urban traffic	4.4	2.4

Figure 3

Figure 3

We used a standard scale [ISO 15666:2003, [1], p. 15,666] to assess listeners' annoyance in response to several types of environmental sounds. Red indicates that sounds were more annoying. In this case, the sound of the breaker was the most annoying sound, with the sound of urban traffic being least annoying. A construction breaker is a heavy duty percussion hammer tool for breaking up concrete and similar materials. Aircraft appears twice because the aircraft sound was repeated in each test, to use as a control signal.

IN THE FUTURE...

In this article, we talked about a few different types of sensor that you can use to measure how people respond to different types of sound. These devices are getting smaller and more practical to use for long durations, so that in the future, we are hoping to bring together all of these ideas, to predict what might happen in our bodies and brains when we are exposed to new types of building noise or transportation noise, like new railways, runways, and the like. We hope that our results will help architects and engineers to make informed decisions and, ultimately, create a more pleasant-sounding world.

ORIGINAL SOURCE ARTICLE

Daly, I., Malik, A., Hwang, F., Roesch, E., Weaver, J., Kirke, A., et al. 2014. Neural correlates of emotional responses to music: an EEG study. *Neurosci. Lett.* 573:52–7. doi: 10.1016/j.neulet.2014.05.003

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YOUNG REVIEWERS

DANIELE, AGE: 16
Sixteen y/o guy who likes IT/Tech stuffs, math and physics and enjoys trying to solve problems that are too hard for a teenager but only realizes it after spending many weeks trying to figure out how to solve them.

TOTS & TEENS, AGES: 10–12
We are a small but mighty class of curious, multilingual learners. We are studying living things, life processes, natural habitats, and environmental damage caused by humans in our second language, English! Some of us love science, there is even a budding scientist amongst us, but some of us are not so keen. We are hoping you can show us just how amazing science can really be.

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MATHEMATICS
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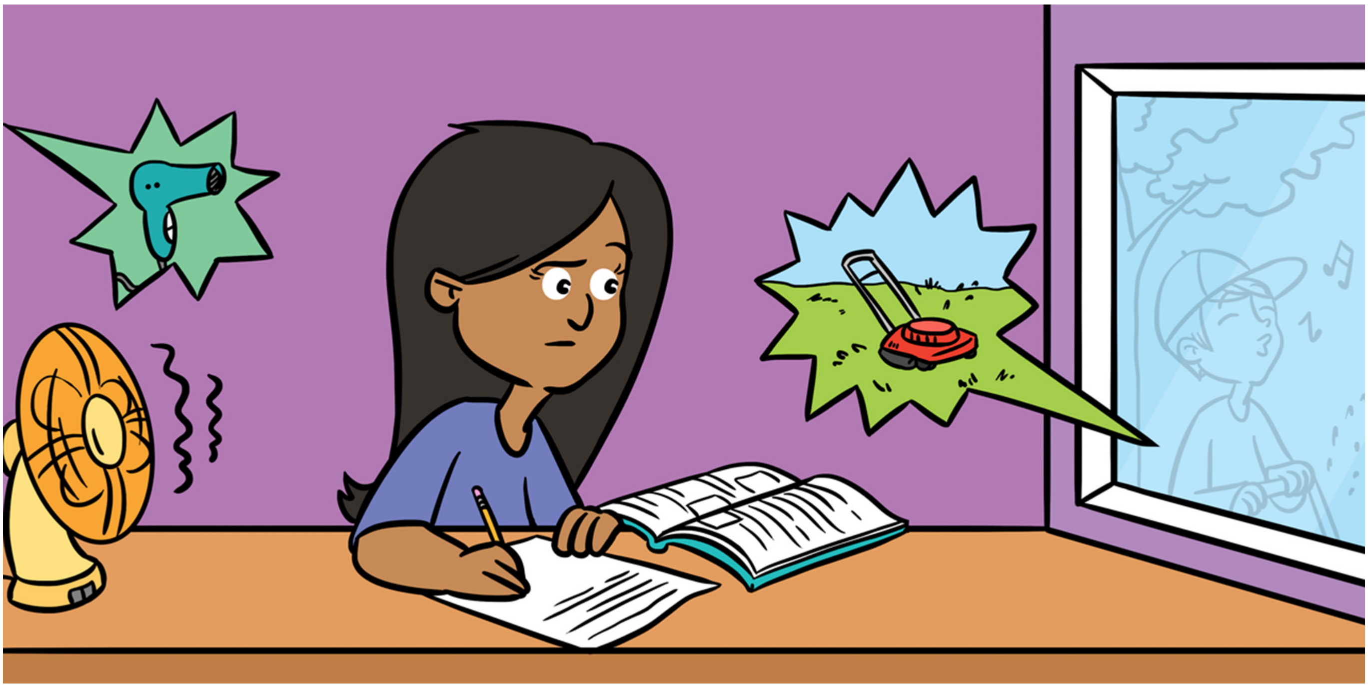

TACKLING NOISE POLLUTION WITH SLOW SOUND

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YOUNG REVIEWER:

GINNY
AGE: 12

Noise pollution can reduce the quality and even the length of our lives, causing around 12,000 early deaths in Europe each year. Devices called resonators can be used to reduce unwanted noise from engines and fans, by cancelling out sound waves. However, the sound waves of low-pitched noises are difficult to cancel because they are very big: sometimes as long as 17 m! To cancel such large sound waves would require an impractically large resonator. One solution to this problem is to make the resonator from a special class of material called a metamaterial. Metamaterials have specially designed structures that give them properties that are not found in ordinary materials. This article explains how we used mathematics to design a metamaterial that slows down sound waves. Slowing the sound allows us to use smaller resonators, so we can cancel lower-pitched noises than we can with ordinary materials.

Have you ever tried to do your homework or read a book while somebody nearby is mowing a lawn or using a hairdryer? The noise can make it difficult to concentrate! Now imagine living close to a busy airport. The European Environment Agency estimates that aircraft noise has harmed the learning of 12,500 European schoolchildren [1].

Unwanted noise can damage our health, too, leading to around 12,000 early deaths in Europe each year, due to an increase in stress-related heart disease.

One way to reduce noise from engines and fans is to include noise cancellation in their design, but noise-cancelling devices can be bulky and impractical. In this article, we describe how we use mathematics to tackle this problem, by designing a material that we can use to make smaller noise-cancelling devices. First, we will look at sound waves and what happens when they combine. Next we will describe how a simple noise-cancelling device works, and why the size of the device matters. Then we will show how our new material, designed using mathematics, lets us shrink the size of a noise-cancelling device.

THE CHARACTERISTICS OF SOUND WAVES

Sounds are caused by vibrations. When an object vibrates, the air around the object vibrates too. The vibrating air molecules make other air molecules around them vibrate and so on, all the way to our ears. Inside our ears, tiny bones vibrate, and our brains understand this as sound. In a sound wave, it is the vibrational *movement* that travels along, and not the air particles.

Air particles in a sound wave are squashed together and stretched apart like the coils in a slinky being stretched and released. Although the particles move back and forth along the direction the wave is traveling, we often draw sound waves as wavy lines going up and down, more like ocean waves (Figure 1A). The height of the line tells us the pressure—how squashed together the particles are at any point. The highest points (peaks) show where the particles are most compressed, and the lowest points (troughs) where they are the most separated.

In our wave drawing, the distance from the highest or lowest point to the center is called the **amplitude**. Amplitude is a way of measuring loudness. It tells us how close together or spaced out the particles are, compared to their resting positions. The bigger the difference, the louder the sound. We measure loudness in units called decibels (dB).

As well as the amplitude, we also measure the **wavelength** and **frequency** of a sound. The wavelength is the distance from a point on one wave to the same point on the next; for example, the distance from the peak of one wave to the peak of the next. The frequency is the number of waves that pass a fixed point in 1 s . It is measured in hertz (Hz), or waves per second. Remember the slinky: if you stretch and release the slinky rapidly, you will create a high-frequency wave. Reducing the number of movements per second lowers the

AMPLITUDE

The maximum distance of a particle in a wave from its resting position. Sound waves with large amplitudes are loud and low amplitude sound waves are quiet.

WAVELENGTH

The length of one wave, measured in metres from a point on one wave to the same point on the next wave.

FREQUENCY

The number of waves that pass a fixed point in 1 s , or the number of oscillations per second. Measured in Hertz (Hz, or S^{-1}).

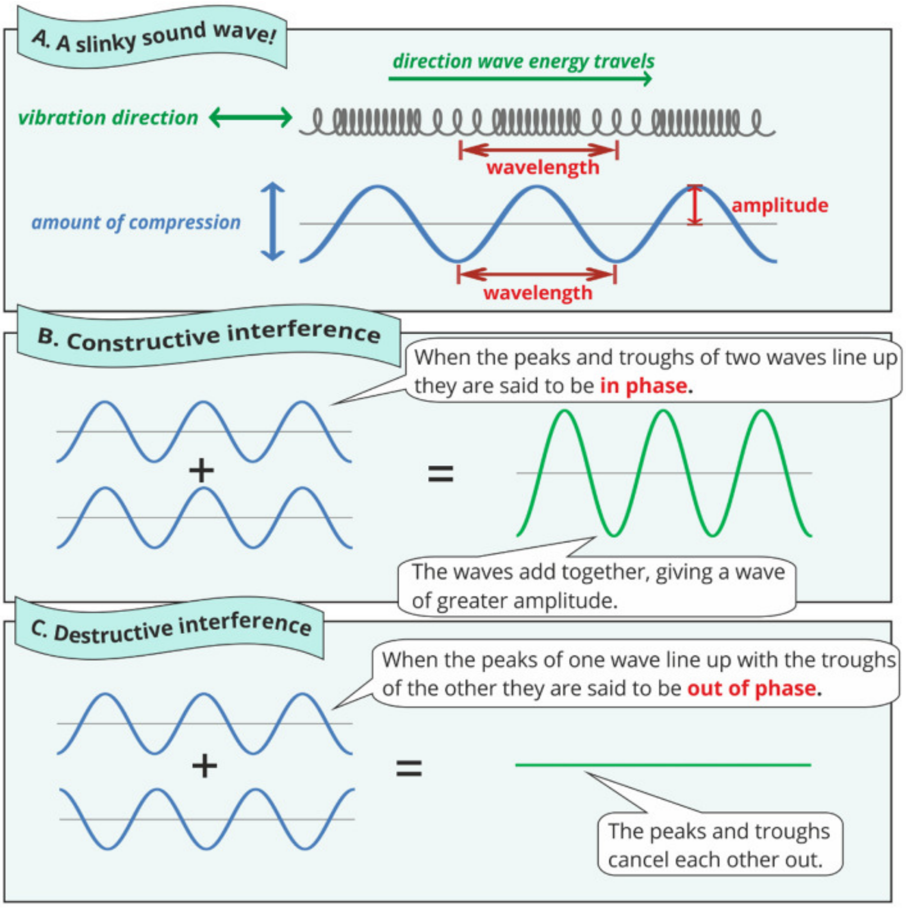

Figure 1

Figure 1

(A) Sound waves are characterised by their wavelength and amplitude. The larger the amplitude, the louder the sound. **(B)** Constructive interference produces a wave of greater amplitude, making the sound louder. **(C)** In destructive interference, waves cancel each other out, making sound quieter.

frequency. Frequency tells us about the pitch of a sound—the higher the frequency, the higher-pitched the sound.

HOW CAN ADDING SOUNDS TOGETHER RESULT IN LESS SOUND?

When waves meet, they affect each other in different ways. We call this interference. The type of interference depends on how the waves line up. Figure 1B shows two waves, positioned so that their peaks line up exactly. We say the waves are in phase. Waves that are in phase add together to give a wave with higher peaks and a bigger amplitude. For sound waves, this gives a louder sound. We call this **constructive interference**.

CONSTRUCTIVE INTERFERENCE

When waves add together so that their peaks and troughs line up, the result is a higher amplitude wave.

Now look at Figure 1C. Here, the peaks of one wave line up with the troughs of the other. We call this being out of phase. The result is that the two waves cancel each other out and you end up with no wave at all! We call this **destructive interference**. For sound waves, destructive interference results in a quieter sound.

DESTRUCTIVE INTERFERENCE

When waves add together so that the peaks of one line up with the troughs of another and the peaks and troughs cancel each other out.

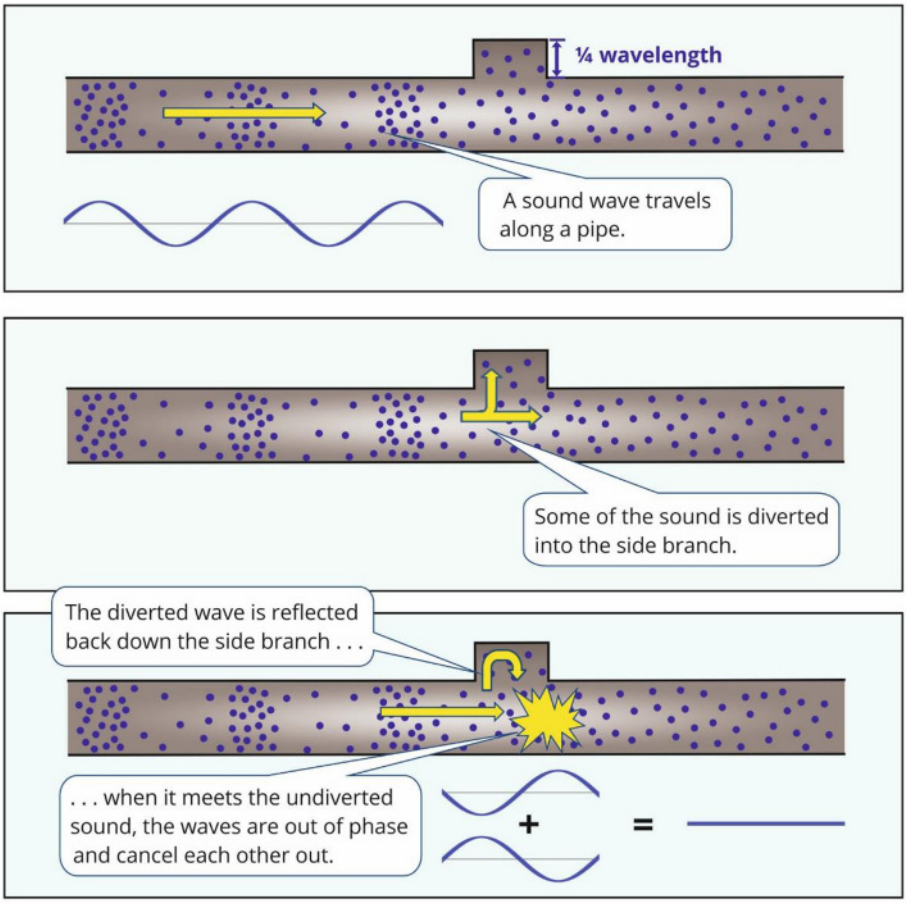

Figure 2

Figure 2

The quarter-wavelength resonator can make sounds quieter by diverting some of the sound. The diverted and undiverted sound waves recombine with destructive interference, quieting the sound that exits the pipe.

NOISE CANCELLATION: THE QUARTER-WAVELENGTH RESONATOR

Many gadgets rely on destructive interference to reduce unwanted noise. For example, noise-cancelling headphones play sound waves that are out of phase with the unwanted sounds. When the waves meet, they cancel. Other devices rely on their geometry to do the work. These include the **quarter-wavelength resonator** (QWR), which can be used to reduce noise made by engines and fans [2, 3].

QUARTER-WAVELENGTH RESONATOR

A noise-cancelling device that operates via destructive interference.

The exhaust pipe on a vehicle takes fumes away from the engine and releases them into the air. But noise also travels along the pipe! A QWR is an extra bit of pipe that branches off the main exhaust. It traps and reflects sound waves. Figure 2 shows how it works. Sound travels down the pipe, some of it enters the side branch, is reflected, and meets up again with the original sound wave. The reflected and original waves are out of phase when they recombine, so destructive interference happens, making the sound quieter.

The length of the side branch is important: for the two waves to be out of phase when they meet, its length must be one quarter of the

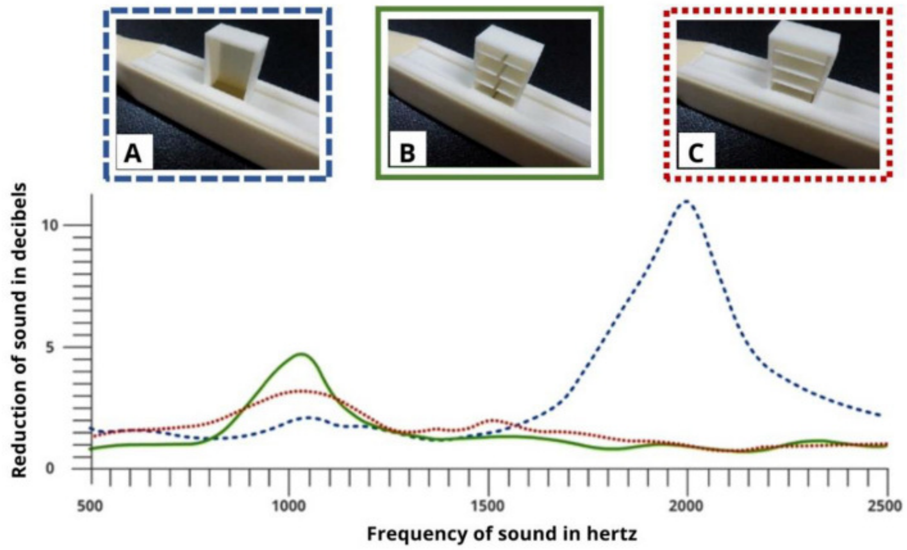

Figure 3

Comparing metamaterial QWRs **(B,C)** with "normal" QWR **(A)**. **(A)** The normal QWR (blue) has a peak at 2,000 Hz, reducing sound at that frequency by about 10 dB. **(B)** This QWR (green) shows a 5 dB sound reduction peak at 1,000 Hz. **(C)** This QWR (red) also reduces sound at 1,000 Hz, but less effectively. The decibel scale is not linear: a reduction of 3 dB reduces the sound energy by half and 10 dB is a 10-fold reduction. The reductions measured in dB are the same however loud the initial sound is.

wavelength of the sound we want to cancel. This is why we call it a quarter-wavelength resonator.

THE PROBLEM OF LOW-FREQUENCY NOISE

So far so good. But what if the sound waves are very long? The side branch must be one quarter as long as the sound wave, so the bigger the wavelength, the bigger our QWR needs to be. And sound waves can be very large! Low frequency sounds have the longest wavelengths, and high frequency the shortest. Humans can hear frequencies as low as 20 Hz, which corresponds to a 17-m-long wave!

The noise from engines can include frequencies with wavelengths longer than 3 m [4]. A QWR would need to be 75 cm long to eliminate a 3 m long sound wave by destructive interference. Large devices add weight and cost, not to mention being difficult to fit!

DESIGNING MATERIALS WITH MATHS

METAMATERIAL

A special material with unusual properties that are normally determined by its geometrical structure.

We used mathematical modelling to design special materials to help solve this problem. Our materials are called **metamaterials**. The properties of metamaterials depend on their shape and structure, rather than the stuff they are made of. Metamaterials interact with waves in ways not seen in ordinary materials [5]. We used a 3D printer to make QWRs with metamaterial structures inside them (Figures 3B,C). Both are 4 cm long with thin, oval shapes stacked inside. One has a very narrow gap at each side, while the other has a slightly wider gap in the centre. We also made a normal QWR without a metamaterial structure inside (Figure 3A).

Our metamaterials slow down sound to about half its normal speed. They do this by stretching out the space through which the sound wave travels. Slowing down the sound has an effect you might not expect: it makes the metamaterial resonators cancel sound at lower frequency than the normal QWR does. This is because of the mathematical relationship between wavelength, frequency, and the speed of sound:

$$\text{speed of sound} = \text{wavelength x frequency}$$

For a QWR we can rearrange this equation so that:

$$\text{frequency of sound reduced} = \text{speed of sound} \div \text{wavelength}$$

Where the wavelength is four times the length of the QWR. In this equation if we halve the speed of sound, the frequency of sound reduced will be halved. So we expect our metamaterial resonators to cancel sound at half the frequency compared to a normal QWR.

OUR RESULTS

Figure 3 shows what happened when we tested the three QWRs. We measured how much loudness was lost at a range of frequencies. We expected the metamaterial QWRs to reduce sound at half the frequency compared to the normal resonator, and indeed, both metamaterial QWRs did so! The metamaterial in Figure 3B has the wider gap in its centre rather than two narrower gaps at the edges, and this small difference makes it more effective than the metamaterial in Figure 3C; it reduces sound by 5 decibels. This is a significant difference, similar to the drop in loudness you would get by increasing your distance from the source of a sound by 1.8 times (for example, if you are 100 m away, it would be like moving to 180 m away).

WHY DOES HALVING THE FREQUENCY MEAN SMALLER DEVICES?

We know that the lower the frequency of a sound wave, the longer its wavelength. If we halve the frequency of a sound in the air, we double its wavelength. QWRs normally eliminate sounds with wavelengths four times their length, but our metamaterial QWRs eliminate sounds with wavelengths eight times their length. Instead of *quarter*-wavelength resonators, we could call them *eighth*-wavelength resonators! So, with a metamaterial, we can halve the length of the noise-cancelling device needed for a given frequency. This could save space and resources and allow us to reduce nuisance noise at lower frequencies than possible with everyday materials. Our research is a step toward a quieter future!

ORIGINAL SOURCE ARTICLE

Rowley, W. D., Parnell, W. J., Abrahams, I. D., Voisey, S. R., Lamb, J., and Etaix, N. 2018. Deepening subwavelength acoustic resonance via metamaterials with universal broadband elliptical microstructure. *Appl Phys Lett.* 112:251902. doi: 10.1063/1.5022197

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWER

GINNY, AGE: 12

Ever since I was a little girl, I grew up in the world of science and I found my love for math and computers. I decided to work as a Reviewer as it would give me the opportunity to learn how scientific papers are published. I love to read and be with my friends. I am so excited to see what adventures are in store for me in the future.

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I am a professor of applied mathematics and I lead the Mathematics of Waves and Materials research group at the University of Manchester. I did a maths degree and then a master's in applied maths, focussing on how maths could be used to model and understand the world around us. In my Ph.D. studies, I used maths to design new composite materials to study how materials could be used to absorb sound. I now work on many projects related to understanding how we can design materials to manipulate sound and other forms of waves. *william.parnell@manchester.ac.uk

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I studied for an undergraduate degree in maths at the University of Manchester and then stayed there for my Ph.D. My Ph.D. was focused on how we can design materials to change our perception of sounds, for example by reducing the volume of a noise or making it sound further away. Since finishing my Ph.D., I have started writing software for embedded devices at a technology company in London called TG0.

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I am public engagement manager for the Mathematics of Waves and Materials research group at the University of Manchester. I earned a Ph.D. in chemistry, researching how metal-containing molecules interact with light, and an M.Sc. in museum studies, in which I examined how chemistry is portrayed in science museums. Since then, I have worked in various fields, including science museums and nanotechnology. The mathematicians I work with now research the mathematics of waves, and how waves and materials interact. I help them communicate and explain their work.

frontiers FOR YOUNG MINDS

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COUNTING ANIMALS BY RECORDING THEIR VOICES

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YOUNG REVIEWER:

ROSELLE
AGE: 13

Across the world, our wildlife is under threat. Global warming, farming, fishing, buildings, and roads are eating up or damaging wild spaces where animals live. Animals like the vaquita, the world's rarest marine mammal, are on the brink of extinction. To look after the wildlife that we still have, conservationists need to know how many animals there are, and how populations are changing over time. But how do you work out how many gibbons are left in the rainforest, or how many porpoises there are in the sea, if you cannot see them? We work out population sizes by recording and counting the calls or songs animals make. We then use this information to help conservationists make better decisions about how to look after some of our rarest and most endangered species, now and into the future.

HOW MANY ANIMALS?

People across the world are working to protect wild animals. To do this, they need to work out how many animals are alive now and whether their numbers are increasing or decreasing. Scientists must find ways to count animals at a given place and time. But counting animals is actually much harder than it seems, and scientists are constantly searching for better ways to gather the information they need. One relatively recent method for counting animals is called passive acoustic monitoring (PAM) density estimation (DE), so **PAMDE**. This method enables scientists to count animals by listening to the sounds they make [1]. Many animals use sounds to communicate or to sense the environment around them.

PAMDE

Passive acoustic monitoring density estimation, the use of sounds to estimate animal density. One example is cue counting.

If you were to enter a room with your eyes closed, you could probably guess the number of people inside without even thinking about it. Your brain could work this out by using information on the overall sound level in the space, and the knowledge that every person has a unique voice. We can use the same idea to estimate numbers and density of animals in certain situations. **Density** is the number of animals in a particular area. However, listening to sounds in a small room is much easier than hearing calls from animals that might be a long way away. But if you know the size of the area you want to study, you can count animals in a small part of that area and use your results to estimate the total number of animals in a larger space. For example, if you are trying to determine how many lions live in 100 square km of the African savannah, you could count all the lion roars in 5 square km, then multiply your answer by 20 to estimate how many lions there are in total.

DENSITY

The number of animals per unit area. If you multiply a density by an area, you get the number of animals (abundance) in the area.

But how do you know if the five roars you counted came from five different animals or from just one noisy one? Well, if you know how often lions tend to roar, you can make a good guess! It is also important for scientists to become experts at recognizing the different sounds made by the animals they are studying. Otherwise, for example, they might think an African wild dog's bark was actually made by a hyena. How good we are at recognizing a sound as a sound of interest is fundamental. If we treat every single detected sound as a sound of interest, when some of these were not produced by the animal we are studying, we could overestimate how many animals there are.

"SEEING" SOUND

Sound waves can travel through solids, air, and water. A sound can be described by how long it lasts (duration), how many times a sound wave is produced per second (frequency), and how loud it is (intensity). Low-frequency sounds, such as a blue whale song, travel further than high-frequency sounds. The distance the sound travels is also affected by what it is traveling through. For example, sound travels further through water than it does through air. In fact, the distance over which a sound can be detected is a combination of the substance it travels through, the intensity of the sound, and the frequency of the sound (Figure 1).

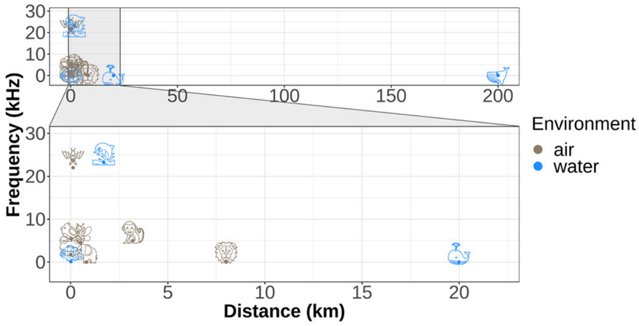

Figure 1

Figure 1

Animal species produce a wide variety of sounds. These sounds are of different frequencies and can travel different distances. Examples on this graph include insects, amphibians, fish, birds, elephants, primates, carnivores, dolphins, and whales. You can see that whale sounds, for example, are low frequency and travel long distances, while bats have high frequency and travel short distances. How far a sound travels will influence how we can use it to estimate density.

SPECTROGRAM

A two-dimensional representation of sound, showing time on the x axis and frequency on the y axis, with color representing intensity[1].

[1] You can learn more about and play with spectrograms here https://musiclab.chromeexperiments.com/Spectrogram/.

HYDROPHONE

A device akin to a microphone but that allows you to record sounds under water.

A **spectrogram** is a visual representation that enables us to "see" sounds. It shows sound intensity and frequency over a given time (Figure 2). Each animal's call makes a specific pattern on the spectrogram, and scientists can identify animals by studying the pattern of these sounds. We can even tell one species from another! For example, the songs of two fin whales will look similar to each other, but very different from, say, the song of a blackbird. Just as we can tell the difference between whales, birds, and fish by how these animals look, we can also tell them apart by their sounds, by studying their spectrograms.

HOW DOES PAMDE WORK?

To use PAMDE, we must first decide on the area of land or sea we are studying. Then, we need to decide on a suitable way to survey it. This usually involves placing several microphones or **hydrophones** (underwater microphones) around our area of study. We might place these sensors on the ground in a grid pattern and leave them recording for several days, weeks, or months. Alternatively, we might tow sensors from moving vehicles, such as boats, gliders, or drones.

A project called the SAMBHA Project surveyed endangered harbor porpoises in the Baltic Sea, to help conservationists understand how to protect this rare species [2]. A total of 300 hydrophones were placed in the water to record sounds made by harbor porpoises for 1.5 years. All together, they produced 300 × 1.5 years = 450 years' worth of recordings! Obviously, one person would not be able to listen to all of this! Luckily, we can use computers to identify the sounds for us. We can use a technology similar to the one used by mobile phones to recognize faces. This technology helps us determine how many porpoise calls are recorded over a particular length of time. Next, we use our data to figure out how many individual porpoises are present in our study area.

Our sound-detection technology tells us whether each sound we record belongs to our animal of interest. The sounds that we detect

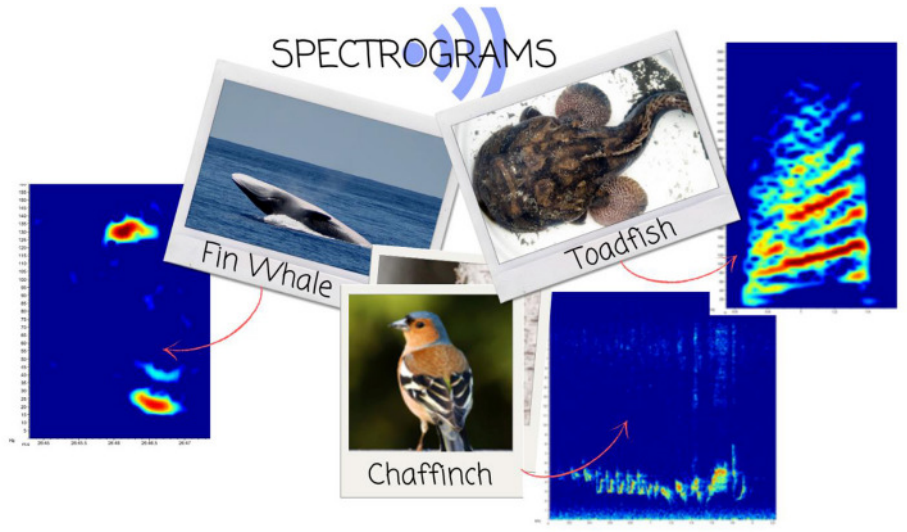

Figure 2

Figure 2

Fin whale, toadfish, and chaffinch photos and their spectrograms. A spectrogram is a representation of sound, in the x-axis you have time and in the y-axis you have frequency, and the colors represent intensity. Here darker colors (yellow/red) represent higher intensity. (Photograph credits: fin whale IMAR/Azores Whale Lab; toadfish Clara Amorim; chaffinch: Creative Commons CC BY-SA 4.0 (https://commons.wikimedia.org/wiki/File:Fringilla_coelebs_chaffinch_male_edit2.jpg, image cropped for composition). Spectrogram credits: André Matos. Audio 1. This fin whale recording from the Azores, Portugal, was used to make the fin whale spectrogram (Recording credits: IMAR—Instituto do Mar / Azores Whale Lab). https://youtu.be/wY8G79J5Ac4. Audio 2. This chaffinch recording from the Companhia das Lezirias, Portugal, was used to make the chaffinch spectrogram (Recording credits: Ana Leal). https://youtu.be/eV0Q5C6R8uc. Audio 3. This toadfish recording from the Tagus estuary, Portugal, was used to make the toadfish spectrogram (Recording credits: Paulo Fonseca). https://youtu.be/myHpOqvGdq4.

are a mix of the sounds made by the animals we are studying and **false positives**, which are other sounds that are mistakenly identified as our animals' sounds. False positives can be for example sounds made by other animals or man made. We must work out the number of false positives to make sure our final estimates are accurate.

We also need to know the size of the area that the sensors are sampling. Detecting 100 sounds in 10 minutes might correspond to low porpoise density if the sounds come from up to 10 km away. But if we only hear sounds that are up to 10 m away, then 100 sounds in 10 min would probably indicate a high density of porpoises. Estimating the area each sensor covers is hard. To help, we use something called a **detection function**, which helps us work out how likely we are to hear a sound of interest at any given distance from the sensor (Figure 3). We can estimate the detection function using either a computer model of how sound moves [3] or by using data from studies of animals in known positions [4].

Finally, **sound production rate** is fundamental. Imagine we wanted to figure out how many people were in your classroom by recording the number of words spoken. First, we would need to know how long your lesson is. Let us say it is 1 h. Then, we need to know roughly how many words each person in the room is likely to speak during an hour. If, on average, students speak 10 words per hour, and we record 300 words in total, we can estimate that there are 300/10 = 30 students. By getting the average word production rate, we can tie the total number of words back to the number of students. The same happens when using PAMDE to estimate animal density in the wild. However, working out how many "words" a whale produces in an hour might be much harder than doing so for your friends. This is a main topic of our current research[2] .

[2] For more info on this project, check out this site: https://accurate.st-andrews.ac.uk/.

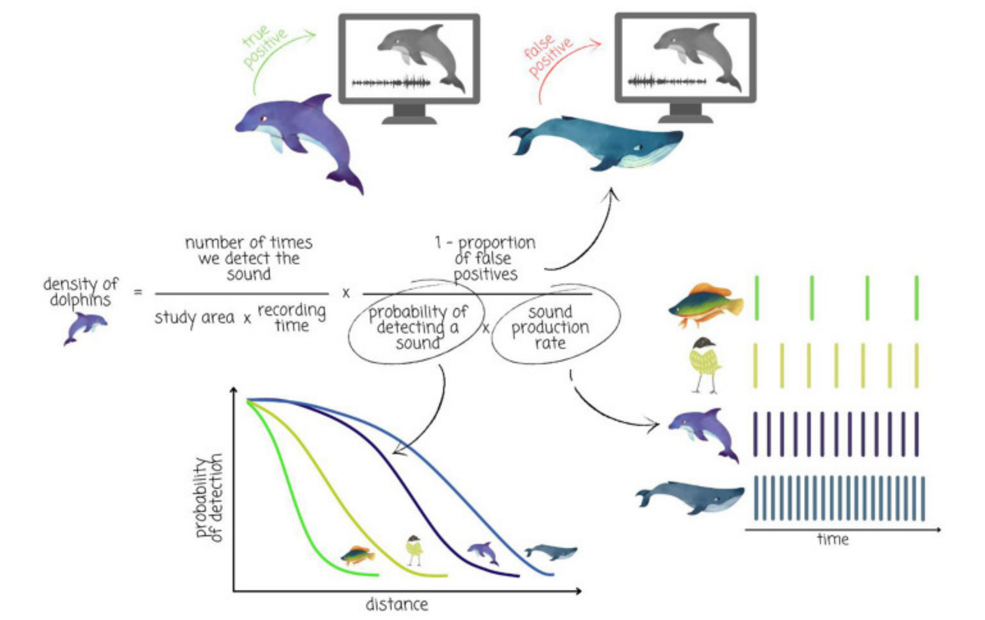

Figure 3

Figure 3

Estimating dolphin density by counting their sounds. For cue counting, we use the number of dolphin sounds detected in a specific area and over a specific time period. We convert these sounds into a dolphin density estimate. To get the density estimate, we must first estimate the probability of detecting a sound, the sound production rate, and the proportion of false positives. For illustration, we present the detection function and the cue rate of hypothetical fish, bird and whale besides those of the dolphin we are interested in.

FALSE POSITIVE

A sound that was considered at first to be of the species of interest but turns out it is not. Could be a sound made by another species, or a man made, or just noise.

DETECTION FUNCTION

The probability of detecting an animal as a function of its distance to a detector. In PAMDE the detector might be say a human, a microphone, or a hydrophone.

SOUND PRODUCTION RATE

The mean number of sounds an individual produces per unit time. A fundamental quantity to estimate animal density from number of detected sounds.

PUTTING IT ALL TOGETHER

A variety of methods exists to estimate animal density from PAMDE. We will concentrate on a method called **cue counting** [2]. Using cue counting, we count the number of acoustic (sound) cues and convert them to animal density (Figure 3). Imagine you are estimating dolphin density in a large region. You have a load of sensors that can hear sounds within a circle of 1 km^2 around each of them. Imagine you have 20 sensors, which you spread in a grid across the area of interest, covering 20 km^2. You set your sensors to record for 10 days and identify 120,000 sounds that you think are made by dolphins. If a dolphin produces an average of 100 sounds per day, each dolphin will produce an average of 1,000 sounds in 10 days. So, you might think there were 120 dolphins there.

But what if you do not hear all the sounds made by every dolphin? Imagine you only hear half of all the sounds that each dolphin makes. If you missed half the sounds, you will have counted only half the number of dolphins. In our example, this means that there were actually 240 dolphins present, not 120. But we still need to account for false positives: the sounds that are not dolphins. Let us say that two in ten of the sounds were not actually made by dolphins, which means only eight in ten sounds were. In other words, of the 240 dolphins you think you counted, some were not actually dolphins at all. So, in the end, we only have $240 \times 8/10 = 192$ dolphins in 20 km^2 which is the same as 9.6 dolphins per km^2. We can put all these calculations together in a mathematical formula (Figure 3). You can do the maths if you want, but you do not have to!

CUE COUNTING

The process of counting animals by counting the number of cues (e.g., sounds, nests, dung, whale blows) they produce and converting it to population density.

WHY IS IT IMPORTANT TO ESTIMATE ABUNDANCE?

Counting animal numbers is vitally important if we want to understand animal populations and how they change over time. This helps conservationists make better decisions about how to care for animals in the future. Using PAMDE has several advantages over visual surveys, in which people look for animals. Without disturbing the animals, we can survey continuously for long periods of time, which allows us to count animals at night, in bad weather, or in the sea or other remote places that humans cannot easily get to. As an example, by counting the numbers of vaquitas, which are small, endangered porpoises from the Gulf of California [5], PAMDE has helped scientists to understand how critical the state of their population is. These studies are helping persuade the government to pass laws to reduce illegal fishing practices that harm these rare porpoises, to prevent them becoming extinct. Valuable work indeed!

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWER

ROSELLE, AGE: 13

I am 13 and I really love animals. I started out rearing stick insects then I moved onto praying mantises. Now I have moved onto bunnies and tropical fish. I am really interested in environmental issues and I am trying to persuade my family to go vegan. When I am not trying to save animals or the environment, I like to sing and dance.

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Luisa F. Dornellas finished her biology degree at the Faculty of Sciences of the University of Lisbon and is currently taking the International Masters in Applied Ecology given by the University of Coimbra and the Christian-Albrechts-Universität

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Anaís Guerra has a B.Sc., in Biology and is now enrolled in a master's degree Science Communication at NOVA University of Lisbon. She is a very resilient person, loves working as a team and believes that knowledge and education are key factors for our community to thrive on the home we call Earth. Therefore, as she steps into a new chapter, she aims to focus in communicating science in a way that is understandable to everyone, while deepening her knowledge about the ecology, wildlife, and the steps our society can take to protect them.

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Carolina S. Marques has an environmental biology degree with a minor in statistics and operations research from the Faculty of Sciences of the University of Lisbon. She is interested in almost everything that involves statistics, mathematics, and ecology, in such areas as passive acoustics and population dynamics. She is currently working for the ACCURATE project. In the future, she plans to follow the field of statistical ecology. She is also a volunteer at the Lisbon Zoo, where she has worked with animals like red pandas and macaws.

BEATRIZ TEMPERO

Beatriz Tempero is a Marine Biology master student at the University of Algarve. Currently working as a marine environmental educator, she aims to raise awareness amongst people of all ages regarding the future of our planet's biodiversity. Driven by curiosity and nature, she wishes to pursue her studies on topics like human impacts on marine ecosystems, animal behavior, and statistics. Beatriz was first introduced to the amazing underwater world at a young age, but rapidly transformed her passion into the purpose of her studies.

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Maria Zacarias has a bachelor's degree in Biology (University of Lisbon) and is now finishing her master's degree in Science Communication at NOVA. Her two main interests are ecology and communication, and to combine the two, she is hoping to pursue a career in science communication. She is a very imaginative and creative person, and hopes to pass on reliable information to the public about science in original and creative ways.

CARYL HART

Caryl Hart is an award-winning children's author who has published over 50 fiction and non-fiction books for children aged 0–11. She also runs creative literacy workshops for schools, libraries, communities, and festivals and is published all over the world. Caryl has a bachelor's degree in biology and worked in environmental conservation and education for 8 years.

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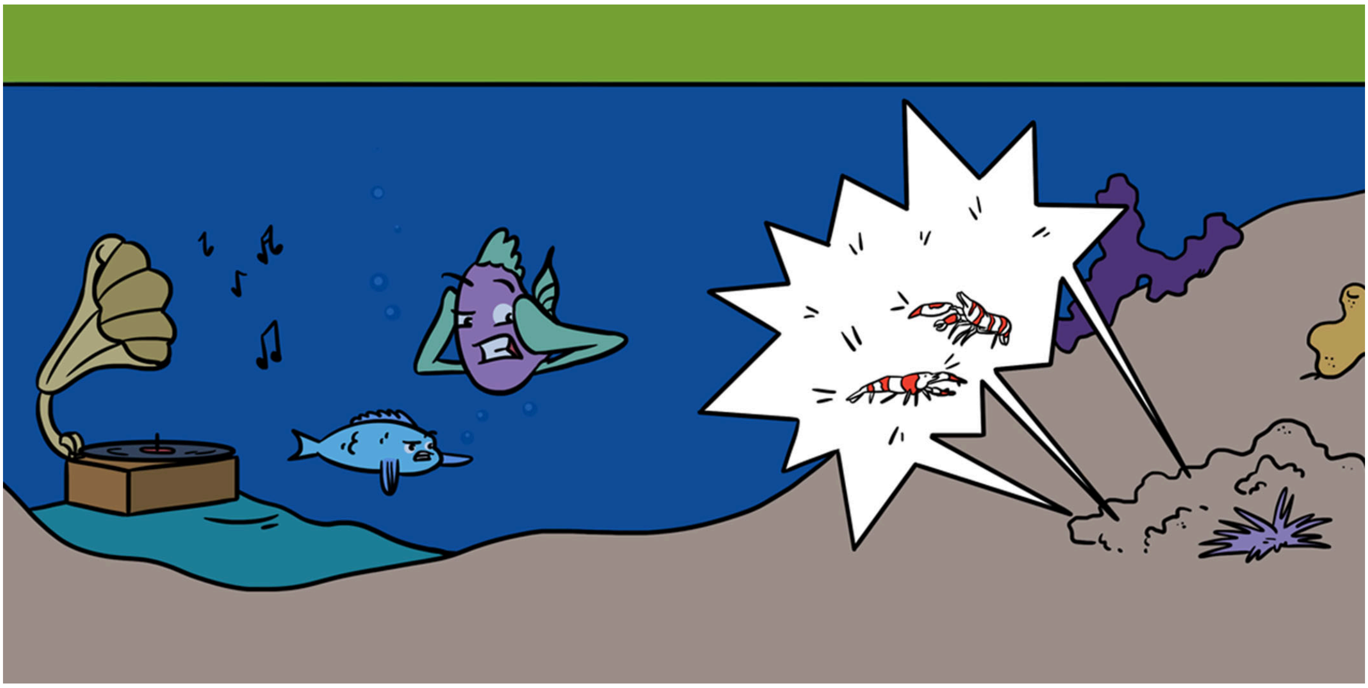

SNAPPING SHRIMP AND THEIR CRUSTACEOUS CACOPHONY

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YOUNG REVIEWERS

ST OSCAR ROMERO CATHOLIC SCHOOL

AGES: 12–13

We humans are a noisy bunch. Our sounds fill the land and air around us, and even the oceans and seas. But we are not the only ones filling the sea with sound. Tiny snapping shrimp, also known as pistol shrimp, are some of the loudest animals in the ocean! They capture their prey by blasting it with a powerful shockwave from an enlarged claw. While the sound from each individual shrimp is small, the noise they make as a group has been known to mask the presence of submarines! How does something so small make such a loud noise? How can scientists use this noise to better understand the health of the seabed?

SNAPPING SHRIMP

Snapping shrimp, also known as pistol shrimp, are not at all like the little pink prawns that some people like to eat. They have a giant claw that gives them an uneven look (Figure 1). Snapping shrimp produce powerful **shockwaves** by snapping this oversized claw. The resulting

SHOCKWAVE

A wave of high pressure that moves faster than the speed of sound.

shockwave is used to communicate with other shrimp, to protect themselves and to hunt and kill their prey.

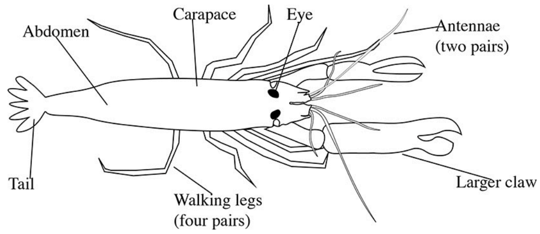

Figure 1

Figure 1

Snapping shrimp are crustaceans and typically have one claw larger than the other.

There are over 600 species of snapping shrimp in our oceans. They are part of the group of animals known as **crustaceans**. Snapping shrimp are the only marine **eusocial** animal, meaning they live in highly organised colonies, like those of bees, ants and mole-rats [1]. These shrimp can be hard to see because they like to hide amongst sponges, corals, stones and shells. They live in areas of the sea near to land where the water is warm and shallow. Snapping shrimp are found around Australia, Hawaii, the Korean peninsula and the Mediterranean Sea. Recently, due to global warming, snapping shrimp have been discovered on the coasts of the United Kingdom, an area once too cold for their survival.

CRUSTACEANS

A group of animals with hard exoskeletons, two pairs of antennae, joined legs and gills for breathing. Includes lobsters, crayfish, shrimp, and true crabs.

EUSOCIAL

Animals that are highly organised into groups or colonies, in which only a few individuals have offspring and those offspring are cared for by the group.

Snapping shrimp can grow to 6 cm in length but some can be as long as 10 cm. Their giant claw can grow to half their body length [2]. Despite their shy nature, these crustaceans are some of the loudest animals in the ocean! Scientists used to think that the loud snaps that these shrimp make came from the upper and lower parts of the giant claw banging together. But more recently, high-speed cameras and underwater microphones called **hydrophones** have been used to analyse the snapping claw in more detail [2].

HYDROPHONE

A type of microphone that has been designed to measure underwater sound.

Figure 2 shows a recording of the sound made by a shrimp snap. Scientists found that, at the beginning of the recording, the shrimp is already in the process of quickly slamming its big claw shut—this takes about half a millisecond. This rapid movement forces a jet of water to whoosh away from the claw at high speed, which, in turn, generates a small bubble. The bubble grows to around 7 mm wide. It is the collapse of the bubble that makes a short but loud snapping sound that generates a big spike in sound pressure, which is the pressure caused by sound as it moves through the water. The bursting bubble creates a shockwave that stuns or kills a shrimp's prey.

A single snap can go unnoticed in the sea, but a large group of snapping shrimp can create a continuous sound resembling the crackling of burning twigs or the hiss of Creepers from Minecraft. Sometimes this sound is loud enough to interfere with the underwater communications of other animals. During the Second World War,

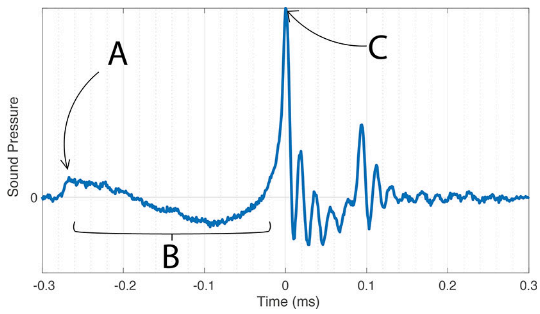

Figure 2

Figure 2

An example of what a shrimp snap looks like over 0.6 ms. The graph measures sound pressure, which is the pressure of the sound wave as it passes through water. At point **(A)**, the claw is slammed shut which creates a small bubble. This is followed by a drop in pressure, shown by **(B)**, during which the bubble grows. The sharp spike at point **(C)** is caused by the bubble popping.

SONAR

A system of sonic echoes used by ships and some animals for navigation. It helps to detect the size, shape and location of other objects including predators, prey or obstacles.

American scientists realised that the noise of snapping shrimp was affecting the **sonar** systems used by Japanese ships. The scientists worked out where large colonies of snapping shrimp lived and used the shrimp noise to hide American submarines from Japanese sonar [3]!

UNDERWATER NOISE

Listening to sounds like music or the wind in the trees can be a nice experience. But some sounds are not very nice to listen to, such as that of a fork scratching a dinner plate or a loud, busy road. These unwanted sounds are often called noise, and too much noise can be bad for our health. It can damage our ears and our hearing and can stop us from sleeping. Have you ever been kept awake by noises? If you do not sleep well, you can feel awful the next day, so we all know that noise can be stressful and tiring. It is not just humans that are affected by noise; too much noise can also damage wildlife. For example, loud traffic noise can affect the times that birds start singing in the mornings and evenings.

We know that noises traveling through the air can be damaging, but what about underwater noise? When having a bath or going for a swim in the sea or a swimming pool, you might have noticed how sounds travel differently through water. Many marine mammals, fish and invertebrates use sound as part of their daily lives. Dolphins, whales, walruses, fish, crabs and shrimp, for example, rely on sounds to get around, communicate and hunt. Some fish even make sounds to attract mates [4].

NOISE POLLUTION

Unwanted sound that can be disturbing or annoying.

Unfortunately, too much noise can have serious effects on these animals, as it masks other sounds and prevents the animals from thriving (Figure 3). Lots of background noise can interfere with animals' senses and can cause confusion and changes in behavior. Human activities such as drilling into the seabed, the movement of boats and ships, fishing and dredging can all damage life on the seabed. This excess noise is called **noise pollution** and can make it harder for animals to communicate, find their way around, hunt or escape predators.

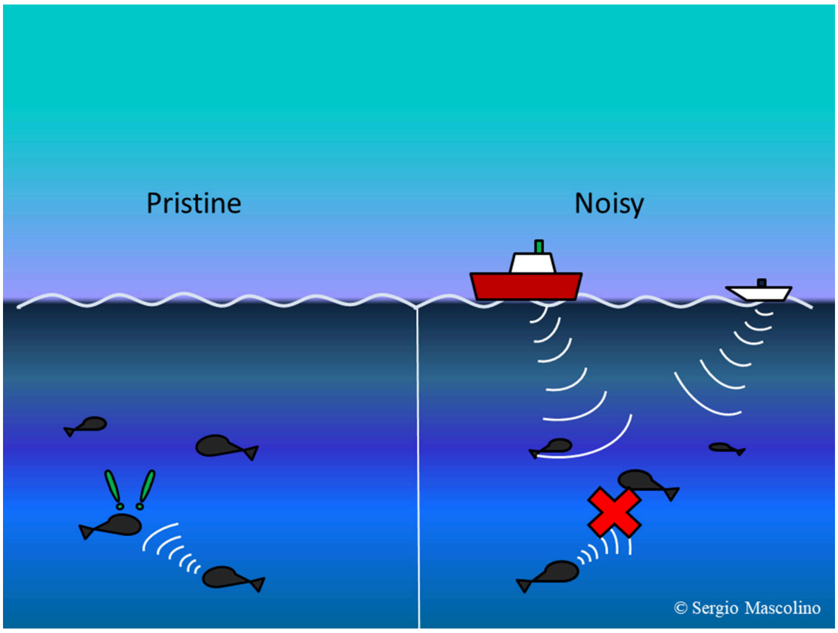

Figure 3

Figure 3

Noise pollution can interfere with the communication of underwater animals.

But just how damaging is noise pollution? Scientists can find it difficult to measure the effects of noise on our underwater wildlife, especially invertebrates [5]. Lots of studies are done on marine mammals and some on fish, but what about other, smaller animals? Could studying snapping shrimp help?

MONITORING THE ECOSYSTEM USING ACOUSTICS

Biodiversity is a measure of the number of different types of organisms, like plants and animals that live in a particular place or habitat. Areas with a high biodiversity are home to many species. Healthy coral reefs and other marine habitats are famous for their amazing biodiversity, but in some places, these habitats are affected by overfishing or pollution.

One way to measure the biodiversity of marine environments is by diving down to the seabed and taking lots of photographs and notes. This can be expensive, time consuming and sometimes dangerous. We know that snapping shrimp like to live inside sea sponges, which are commonly found on coral reefs and other areas. We also know that the healthier the seabed, the more snapping shrimp will live there [6]. Snapping shrimp can tell us something about the condition of the ocean floor. This means that snapping shrimp are good **biological indicators**; they can help us work out how healthy our oceans are. But how do we determine how many snapping shrimp live in a particular

BIOLOGICAL INDICATOR

A type of plant or animal that can be studied to show the health of a whole environment or ecosystem.

ACOUSTICS

The study of sound.

place? We cannot count them by sight because they often hide and are not always easy to see. This is where **acoustics** comes in handy!

We can work out how many snapping shrimp there are by listening to the sounds they make. Scientists use hydrophones to measure underwater noise. Placing hydrophones in carefully arranged positions can help locate the origin of a sound. If snapping shrimp are living in an area, their snaps will be heard on the recordings and their position can be detected.

Shrimp snaps are so loud, quick and full of energy that they can be fairly easy to detect. Scientists can also use groups of hydrophones to check that the sounds they hear actually come from the shrimp and not from some other animal or machine. The result is that acousticians can use sound recordings to count the number of snapping shrimp in large areas without disturbing the organisms that live there. This gives scientists an idea of the overall health of the seabed [6]. Acoustics has also been used this way to study other animals including birds and bottlenose dolphins [7, 8].

Recently, scientists have discovered snapping shrimp living in regions that were once too cold for them. The snapping shrimp are telling us, loud and clear, that our climate is changing, and that our seas are getting warmer. Perhaps we should listen to what they are saying!

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YOUNG REVIEWERS

ST OSCAR ROMERO CATHOLIC SCHOOL, AGES: 12–13

We are a group Y8 and Y9 students at St Oscar Romero Catholic School in Worthing, UK. In total there were 111 of us! We love opportunities to extend our learning beyond the classroom, so it has been great to review scientific papers prior to publication!

AUTHORS

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Cian Jones is a graduate of the University of Salford where he undertook a project to learn how to use acoustics to locate snapping shrimp on the seabed without disturbing their habitat. His work gave him the opportunity to work with scientists from around the world which helped him discover all sorts of exciting things about these fascinating crustaceans. He now works as an acoustic consultant at AECOM where he works toward making the world a quieter place. *cian.jones@aecom.com

CHIARA BENVENUTO

Chiara Benvenuto is a reader in behavioral ecology at the University of Salford. Born in a small village in Italy, on the Mediterranean Sea, she has always been fascinated by the incredible adaptations of aquatic animals (especially fish and crustaceans). Chiara focuses her research on the evolution of mating systems and strategies (including sex change), adaptations to a variable environment (including color change) and behavioral responses to environmental modifications made by humans (including contaminants and noise pollution).

PAUL KENDRICK

Paul Kendrick is an audio machine learning software engineer and researcher. Paul has carried out research into how audio captured in various environments can be analyzed to measure biodiversity. Paul has used artificial intelligence to assess bird activity at the Chernobyl accident site in Ukraine and earlier in his career earned a PhD in room acoustics from the University of Salford. Paul currently works as an artificial intelligence researcher in the professional audio industry, developing intelligent tools for sound engineers.

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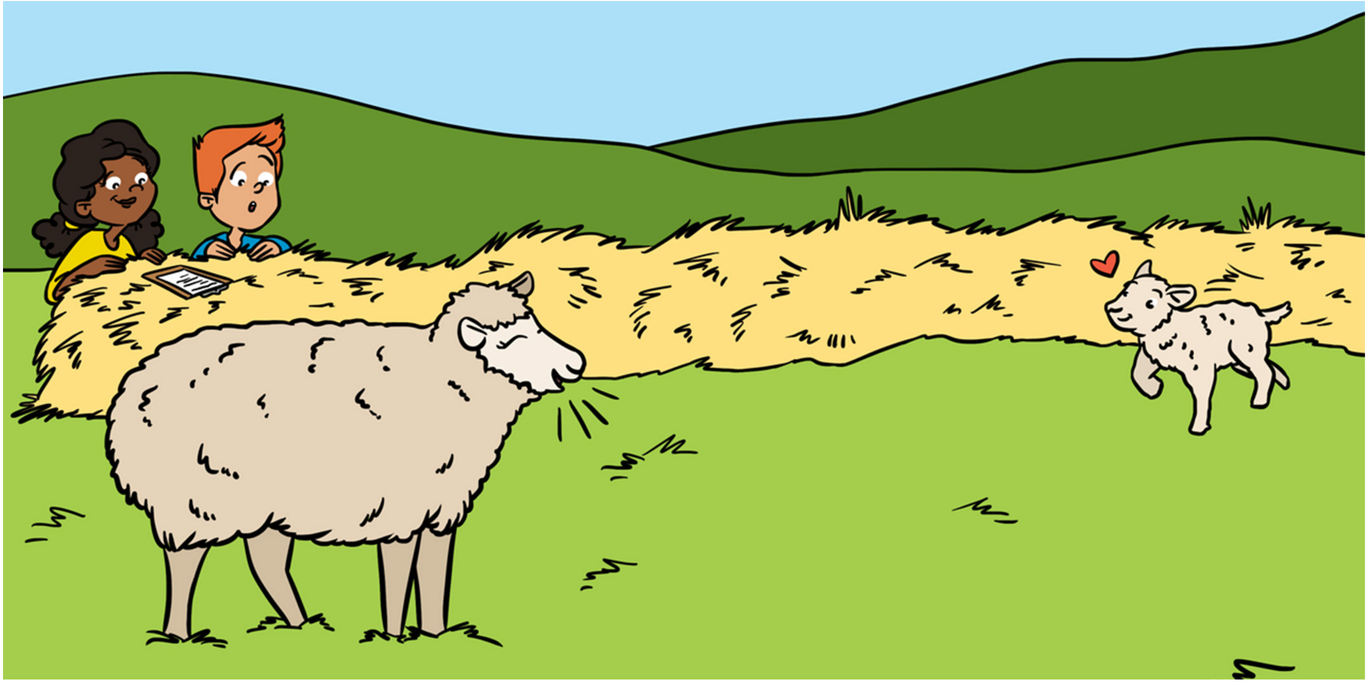

"BAA, BAA": CAN SHEEP TALK TO EACH OTHER?

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CNRS, IFCE, INRAE, Université de Tours, PRC, Nouzilly, France

YOUNG REVIEWER:

TORBEN
AGE: 13

If you have ever been out to the countryside in the spring, you might have heard sheep bleating to their lambs. Sheep also bleat when they are separated from the flock or stressed in some other way. To us, all these bleats sound very similar. But do you think they also sound similar to the lambs? Or do you think the lambs know whose mother is calling and what they are saying? Scientists try to interpret the bleats of sheep by observing their behavior when they hear these sounds. They study the sound waves of recorded bleats to identify each sheep's unique voice and even determine which emotions the sheep are feeling. They also investigate the brain to find out what is going on inside the heads of sheep when they hear and understand the sounds of other sheep. Studies show that sheep really can recognize each other's voices and communicate vocally.

COMMUNICATING WITH SOUND

Do you think that animals other than people can communicate by talking to each other? Or what about communicating in ways besides talking? If you have ever lived with a pet, you probably know that animals are certainly capable of communicating with us. A dog can ask you to throw a stick just by dropping it at your feet. A cat can ask for food by rubbing against your leg. These animals are using behavior to communicate information. If you do not do what they are asking, the dog might bark and the cat might meow, to insist that they really want you to do it, now! Barking and meowing are examples of animals using sounds produced by the mouth (like talking) to communicate. By observing animals in farms, in zoos, or in nature, scientists called **ethologists** (who study animal behavior) have discovered that many animals can communicate using sounds, called **vocalizations**.

ETHOLOGIST

A scientist who studies animal behavior in their natural environments.

VOCALIZATION

A sound emitted by the vocal organ of animals.

INTERPRETING SHEEP SOUNDS FROM THEIR BEHAVIOR

The vocalizations of sheep are called bleats. To interpret the meaning of sheep vocalizations, ethologists often study their bleats and their behavior at the same time, using video cameras and microphones. Observing sheep this way, ethologists showed that lambs and their mothers (ewes) can communicate using what the ethologists called low- and high-bleats. Low-bleats are emitted with a closed mouth, when a ewe and her lamb are close to each other, during caregiving moments such as suckling or licking. High-bleats are emitted with the mouth wide open, when a ewe and her lamb are separated. It is a bit like when parents call their children who are too far away! These high-bleats are also emitted by adult sheep when they are separated from the herd, when they are stressed, and even when their food arrives late! From these observations we interpret low-bleats as comforting vocalizations and high-bleats as distress calls. But scientists do not only *observe* animals, they also create experiments using behavioral tests to investigate how sheep use bleats to communicate.

The **two-choice behavioral test** helps us to understand whether animals can tell the difference between two sounds. If you heard a dog bark and a cat meow, you could easily say which was the dog. If you heard a ewe bleat and a lamb bleat, could you correctly say which was the ewe? These are both examples of two-choice tests, in which you would answer by speaking. But sheep cannot *tell* us the answer, so how do they respond in a two-choice test?

TWO-CHOICE BEHAVIORAL TEST

A test in which an individual makes a choice between two options.

One method that scientists use is to present the bleats in different locations, one on the left and one on the right (Figure 1). When the sheep hear the bleats, they can behave in various ways. Scientists count how many times a sheep chooses to walk toward and stay near the location of each sound. In one study, 48-h-old lambs had to choose between the bleat of their mother in one location and the bleat of an unfamiliar ewe in a different location [1]. The lambs could not see or smell the ewes, they could only hear them. The lambs chose the sound of their mothers much more often than the sounds of the unfamiliar ewes. So, we know that lambs prefer the bleats of their own mothers *and* that they can tell the difference between the bleats of different sheep. From a similar test, we also know that sheep prefer the bleats of their friends who live in the same barn over the bleats of unknown sheep.

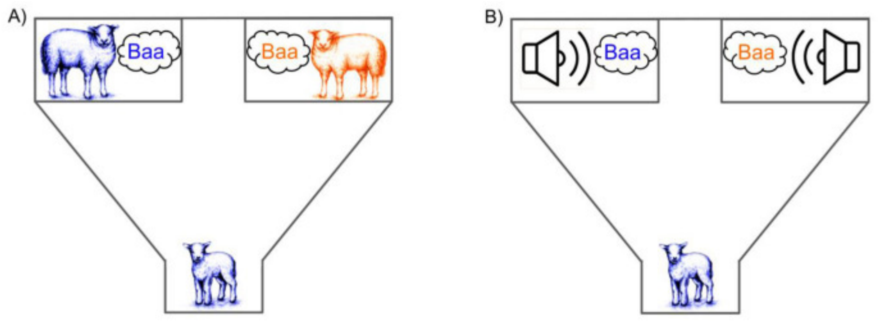

Figure 1

Figure 1

A two-choice behavioral test in which lambs hear two bleats coming from different locations and can show preference for one of the bleats by walking toward it and staying near it. **(A)** A lamb (bottom) hears the bleats of two ewes it cannot see. One ewe is its mother (on the left in blue) and the other is an unfamiliar ewe (on the right in orange). **(B)** The bleats of the mother (left) and unfamiliar ewe (right) are presented from speakers in separate locations, and scientists count the number of times the lamb walks toward each bleat location.

The ewes' vocalizations can be presented to the lambs in two ways. First, the bleats can be made by the actual sheep, which are hidden from the lambs during the test. Alternatively, the bleats can be recorded before the test and presented through speakers (Figure 1). One of the problems with the bleats being made by actual sheep is that the sheep can "say" whatever they want. Scientists cannot control whether the sheep vocalize using high-bleats or low-bleats. So, to test whether lambs preferred high- or low-bleats, it was necessary to use speakers. Speakers were used to play back high-bleats from one location and low-bleats from a different location [1]. The results showed that lambs did not have a preference—it seemed that they liked both. Another good reason to use recorded bleats is that we can also get interesting information from analyzing the sound waves of the bleats.

ANALYZING THE BLEAT SOUND WAVE

Sound waves have physical properties that can be measured and analyzed. One important physical property of a sound is its **amplitude**. High-amplitude sounds are loud, while low-amplitude sounds are quieter. Similarly, high-bleats are louder than low-bleats because they have a higher amplitude. These bleats also have different **frequencies**, which is another important physical property of sound waves. High-bleats have a higher frequency than low-bleats. To understand what different frequencies actually sound like, imagine the sound of a whistle (high frequency) and the sound of thunder (low frequency). **Bioacousticians**, who are sound scientists, study

AMPLITUDE

The amplitude of a sound wave is a measure of its energy, it determines the sound's loudness or volume.

FREQUENCY

The number of waves per second.

BIOACOUSTICIAN

A scientist who studies the sounds produced by animals and the body parts used to produce (mouth), hear (ear), and interpret (brain) those sounds.

amplitude, frequency, and other physical properties to identify the unique signatures of a sound.

When you talk on the telephone, you can recognize the person you are talking to from their voice. You can do this because each person's voice has a **vocal signature**. Like a fingerprint, a person's vocal signature is unique, made up of a unique combination of physical sound properties. By studying the physical properties of sheep vocalizations, bioacousticians have shown that sheep also have vocal signatures that can be used to tell them apart [2].

VOCAL SIGNATURE

The physical properties of the voice that are unique to each individual and which allow them to be recognized.

Can the combination of sound properties in a vocalization also tell us which emotions an animal is feeling? Bioacousticians are currently studying this. If they are successful, they could develop a computer program that could detect various types of bleats by analyzing the combination of sound properties. For example, they might be able to automatically detect when a farm animal is in pain [3], so the farmer could be alerted to help the animal.

But how are these sound properties normally analyzed, interpreted, and identified by other individuals who hear the vocalizations? Well, it turns out that bioacousticians are not the only ones who analyze the physical properties of sounds—brains are also experts at it.

RECOGNIZING A SOUND AS A VOCALIZATION

Before a sound can be recognized as a vocalization, the sound must reach the brain. Sounds first arrive at the outer ear, then the physical properties of the sound (such as its frequency) are sent *via* the eardrum to the middle and inner parts of the ear (Figure 2). In the inner ear, the hair cells of an organ called the cochlea translate the sound into an electrical signal. These hair cells are very thin and fragile and can be broken if you listen to music too loud. The electrical signal flows through the cochlear nerve to the brain. The role of the brain is very important in hearing—brains hear sounds, ears do not. For the animal to identify and understand a sound, many parts of its brain are required.

Each brain part has a different role and it is only the combination of these brain parts working together that allows ewes to hear a sound, to recognize it as a vocalization of their lamb, and interpret how the lamb is feeling. These different parts of the brain have funny and complicated names such as, the geniculate nucleus, the amygdala or the hippocampus. To better understand how the sheep brain recognizes a sound, brain scientists can use techniques, such as functional magnetic resonance imaging [4], that are only just beginning to be used with farm animals.

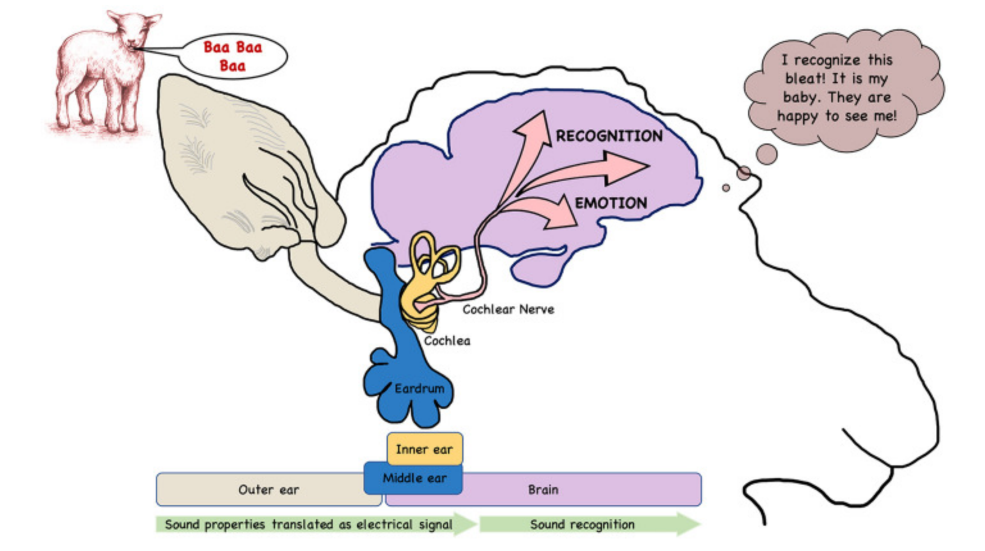

Figure 2

Figure 2

How a sound becomes a voice. When a lamb bleats, it produces a sound wave that travels through the air to its mother's ears. Inside the ear, the sound makes the eardrum (blue) vibrate. These vibrations then travel to the hair cells of the cochlea (yellow), which translate the sound vibrations into an electrical signal. The signal then flows through the cochlear nerve (pink) to the brain (purple). Various parts of the brain analyze, interpret, and identify the electrical signal, so that the ewe knows that the sound she hears is her lamb bleating happily.

CONCLUSION

Sheep, like other animals, can communicate using sounds. By studying their behaviors, ethologists have shown that sheep can tell individual sheep apart from each other just by listening to their bleats. Sheep can do this because each sheep's bleat has its own vocal signature. A bleat's sound waves can also contain information about how a sheep is feeling. Bioacousticians are trying to understand this information to help farmers detect when their animals are in pain, for example. Brain scientists investigate the structure and function of the brain to understand the role the brain plays in vocal communication. To fully understand sheep communication, it is important for ethologists, bioacousticians, and brain scientists to work together. The more we know about the lives of sheep, the better our chances of improving the lives of this farm animal.

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWER

TORBEN, AGE: 13

Torben is motivated, talented, and intelligent. In school, he likes science, math, history, and geography. He loves to read books and is learning Spanish, French, and German. He plays piano and sings in several choirs and has won several local and national music awards. He has a special interest in neuroscience-related topics. His English teacher selected him to report on the COVID-19 crisis. To do so, he wrote a Spotify segment and interviewed his teachers about how the pandemic impacted teaching and learning. He enjoys biking, soccer, hiking, swimming, horseback riding, and other activities that he carries out with his boyscout troop.

AUTHORS

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thesis is about how genetics and environment impact the brain morphology. I like to share my knowledge by helping children and non-scientists understand scientific concepts. *marine.siwia@gmail.com

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I am a researcher at the French National Research Institute for Agriculture, Food, and Environment (INRAE). I am trying to understand how brains help animals to perceive other individuals and how the environment changes the brain. To do this, I conduct behavioral experiments with animals and use techniques that allow us to look into the brain, to see its structure and investigate how it works.

ELODIE CHAILLOU
I am a researcher at the French National Research Institute for Agriculture, Food, and Environment (INRAE). I am studying how the structure of the sheep brain relates to a sheep's emotional behaviors. For more than 10 years, I have organized scientific events for children. I love to share my knowledge with young people and to explain the sheep brain, especially helping children to discover the neurons.

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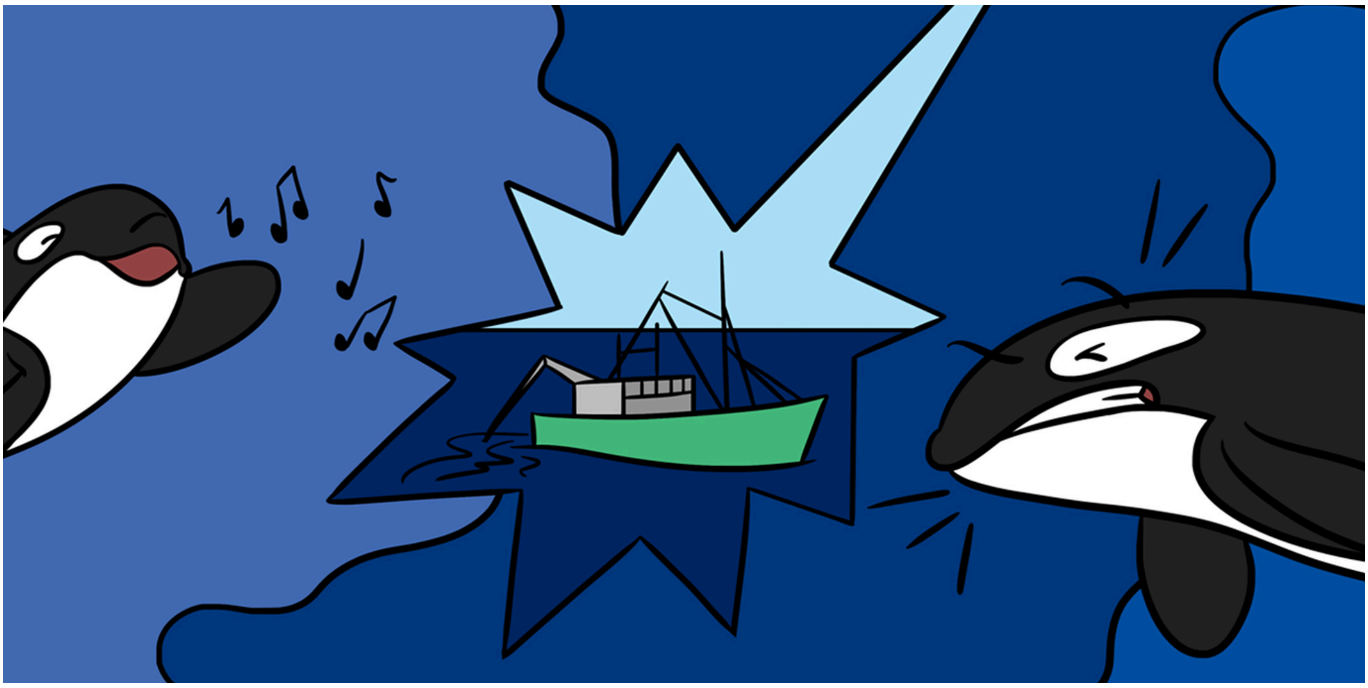

OCEAN NOISE: THE HUMAN FOOTPRINT ON UNDERWATER SOUNDSCAPES

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YOUNG REVIEWERS:

CLASS 2A—SECONDARY SCHOOL LICEO SCIENTIFICO "DUCA DEGLI ABRUZZI"
AGES: 15–16

ST OSCAR ROMERO CATHOLIC SCHOOL
AGES: 12–13

You may have heard that our oceans are under threat due to the impacts of climate change, plastic pollution, and ocean acidification. But there is another threat that must be highlighted—noise pollution. Humans are becoming more and more reliant on the ocean for transportation and renewable energy, but these activities introduce noise. Every fishing vessel, cruise ship, ferry, cargo ship, and jet ski leaves a sound "footprint," meaning our oceans are becoming increasingly noisy places. Many animals, including whales, dolphins, and fish, produce unique sounds—and scientists are looking at how man-made noises are affecting their communication, behavior, and habitats. We hope to discover ways to create harmony between humans and marine wildlife, to reduce the impact of noise pollution on marine ecosystems. In this article, we will introduce how marine species use sound, how noise pollution affects them, and how they are adapting to sharing their environments with humans.

HOW DO WE RESEARCH SOUND?

When people think about the ocean, they often imagine a quiet world, but beneath the surface, oceans are very noisy places!

Sound travels through water at a speed of about 1,500 meters per second. That is three times faster than sounds move through the air, and equivalent to around 30 lengths of an Olympic swimming pool every second! Sound is created by vibrating objects. Objects in the ocean which vibrate create sound pressure waves that compress and decompress the surrounding water molecule, allowing a sound wave to travel through the water. Sounds waves traveling through the water are described by their **frequency** (pitch) and **amplitude** (loudness). High-frequency sounds have a short wavelength and do not travel very far. Low-frequency sounds have a long wavelength and can travel further, especially in water (Figure 1).

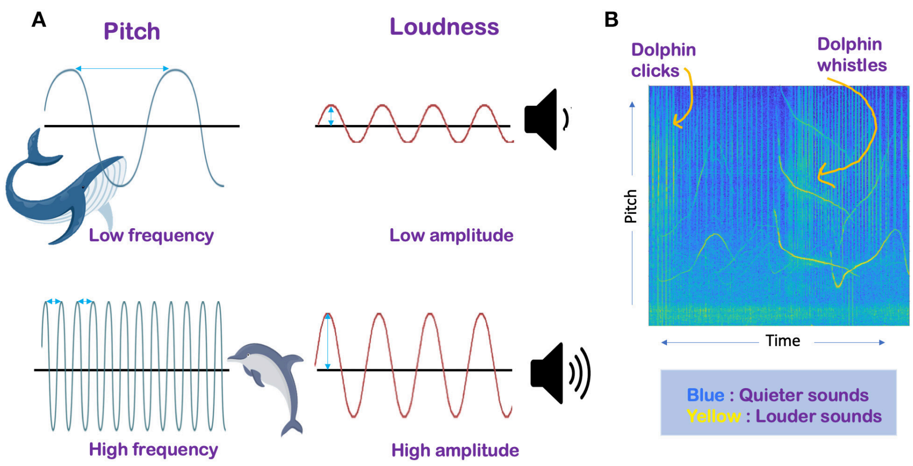

Figure 1

Scientists use underwater microphones called **hydrophones** to record sounds within the ocean. These recordings create a **soundscape**, which is a "picture" of all the sounds in one place at one point in time. Using hydrophones, we can detect weather events like hurricanes and earthquakes, and human activities such as fishing and shipping. By comparing soundscapes from various places, and from 1 year to another, scientists can track animals that travel long distances and look at changes in habitats and ecosystems over time. By understanding how each type of sound spreads underwater, we can predict how far sounds will travel in our oceans and what effects they might have on the wildlife that lives there [1].

WHY IS SOUND IMPORTANT UNDERWATER?

On land, most humans use sight to explore the world around them. Our eyes detect light patterns, and our brains work out what those

FREQUENCY

The number of sound waves that are recorded by a hydrophone at a fixed point in time. High-frequency sounds have a high pitch; low-frequency sounds have a low pitch.

AMPLITUDE

How loud a sound is. Scientists can measure amplitude by describing how high the sound pressure waves are, detected by a hydrophone.

Figure 1

(A) High- and low-frequency sound waves, and high- and low-amplitude waves. Large whales make calls that are low frequency and high amplitude, whereas dolphins make high-frequency calls that are loud, but not as loud as larger whales. **(B)** A spectrogram of a dolphin whistling, with echolocation clicks in the background. Spectrograms are images of sound, with time on the x-axis and pitch on the y-axis, allowing scientists to visualize the ocean soundscape.

HYDROPHONES

Underwater microphones used to listen to the ocean.

SOUNDSCAPE

The combination of sounds created by plants and animals, sounds like wind, rain, storms, earthquakes, and ice-breaking, and sounds created by humans. A region's soundscape can vary over time.

light patterns mean. But light does not reach many parts of the ocean, so many animals rely on sound to "see" each other, to find their way around, and to hunt for food. Seals, fish, crabs, and even plankton all use sound to communicate with each other, but the underwater animal sounds we know the most about are those made by whales and dolphins.

Large whales, such as humpback, fin and blue whales, use low-frequency sounds that can be heard over long distances. Some are stand-alone calls and others form songs! Each whale species has a unique call, which makes it easier for scientists to detect who is who (Figure 2). Toothed whales, such as dolphins, communicate using high-frequency sounds, which we call clicks and whistles (Figure 1). Whistles are used to chat or pass on social information, although we do not yet know what the animals are chatting about! Perhaps they are warning others of danger or telling them where the best fishing spots are! The clicking sounds dolphins make are used for **echolocation**. The dolphin produces clicks that bounce off objects in the ocean, and the sound waves are reflected back to the dolphin (Figure 2). That "echo" tells the dolphin where the objects are and provides information on the size and shape of objects, allowing dolphins to "see" with sound.

ECHOLOCATION

The ability to locate objects using reflected sounds. An animal sends out a series of sounds and listens for the signal that bounces off the object and returns to the animal.

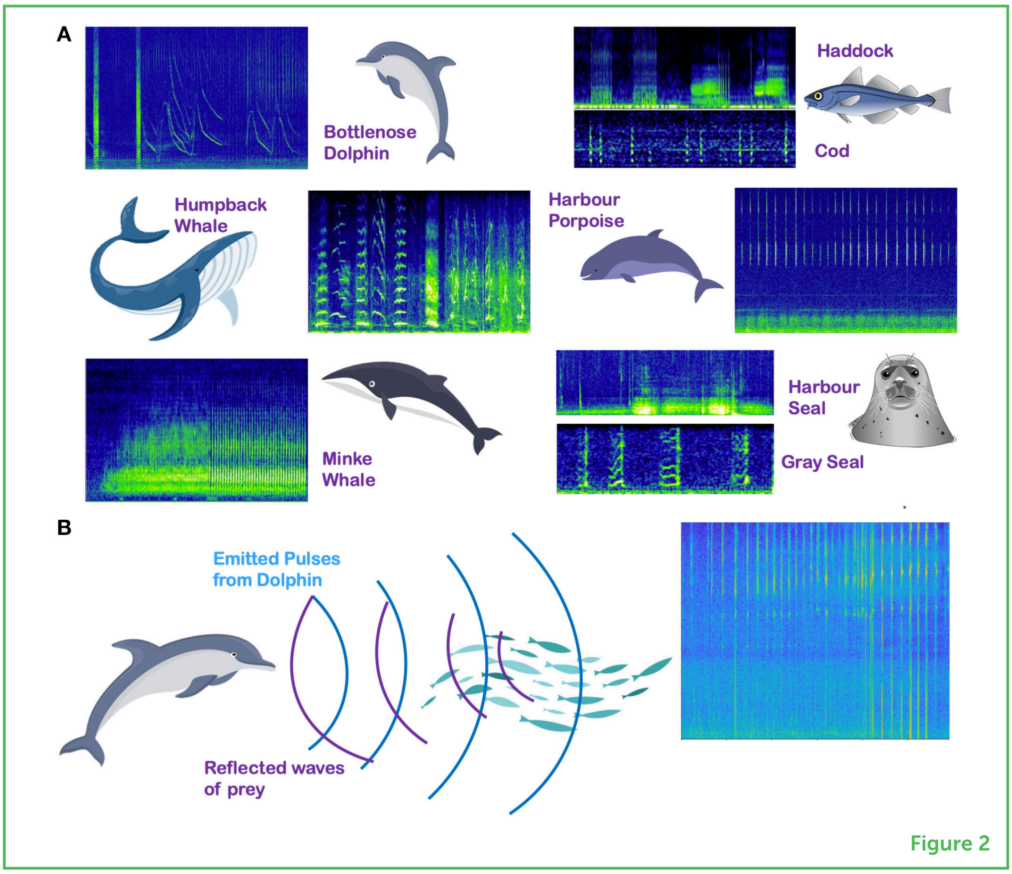

Figure 2

(A) Example of spectrograms of unique calls made by marine mammals, which allow scientists to identify them in the soundscape. Notice how each call type has unique pitch and loudness characteristics. Spectrograms are obtained through the US National Oceanic and Atmospheric Administration[1]. **(B)** Dolphins use echolocation to find food, by emitting clicks.

[1] If you would like to listen to what the animals sound like, head to `https://www.fisheries.noaa.gov/national/science-data/sounds-ocean` where you can listen to the spectrograms.

Using sound to listen to environments is a great way to eavesdrop on other species without affecting their day-to-day lives, which helps us to work out how humans are affecting soundscapes around the world.

THE HUMAN IMPACT ON SOUNDSCAPES

Humans depend on the oceans for transportation, fuel, and creating renewable energy (such as wind farms). The noise these activities make leaves a large "footprint" on the ocean's soundscape (Figure 3). Much of the foods we eat and the things we buy have been transported across the oceans in ships. Every day, around 60,000 ships are moving across our oceans and seas, with 500 ships in the English Channel alone. These ships carry 226 million containers packed with things humans consume, and the ships' engines produce very loud, low-frequency sounds—when a sound produced has a negative effect

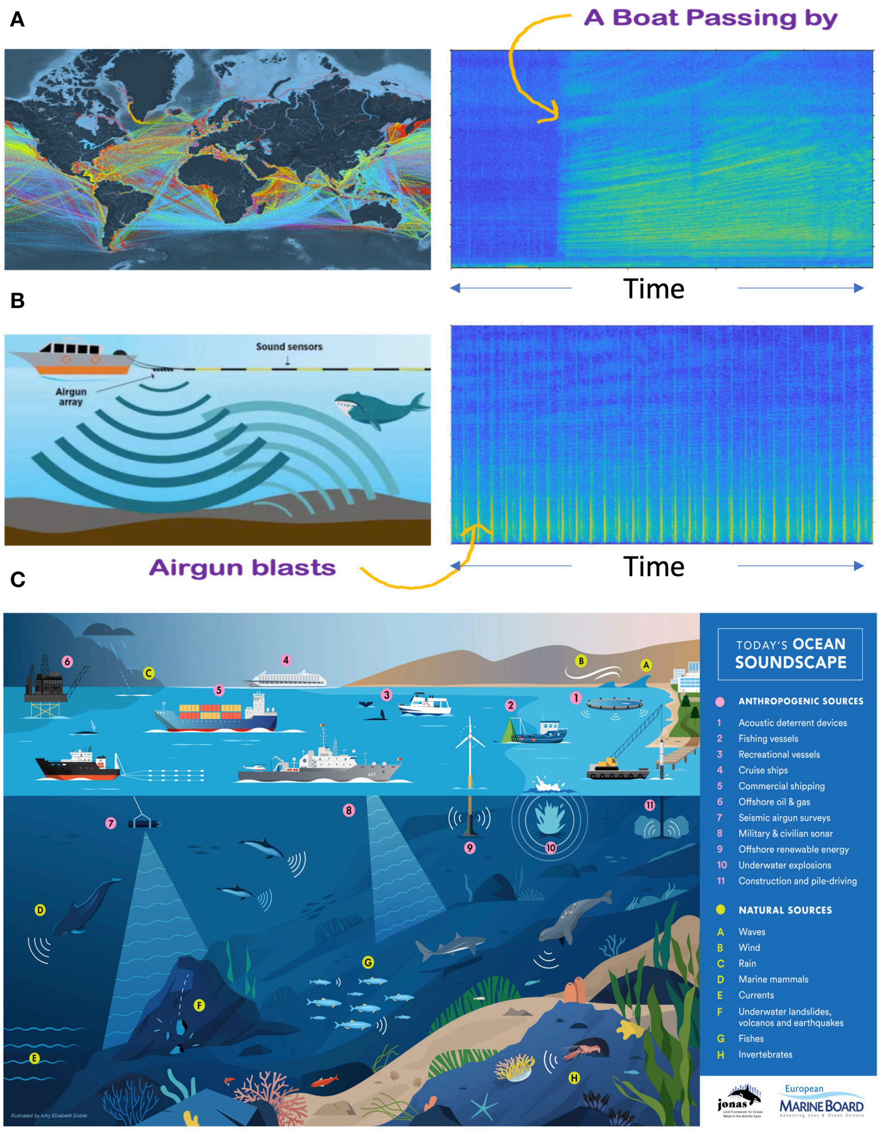

Figure 3

Figure 3

(A) Map of global ship activity per day. Each color represents a different ship type and you can see clear paths across the oceans, where there is a lot of ship noise. The spectrogram illustrates a boat passing by a hydrophone. Notice how bright the color is—this shows how loud the ship is relative to the background sound in that area. **(B)** Airguns are used to explore the seafloor, and their blasts are deafening to nearby wildlife. **(C)** Today's ocean soundscape contains many sources of noise that marine life must face. "Anthropogenic" means human generated (Image credit: the Jonas Project [2]).

on the environment it becomes "noise." Ship noise spreads great distances through the water and interferes with marine animals' ability to communicate and find food. The increasing level of ship traffic is raising the natural sound level of our oceans!

Much of the oil and gas we use comes from reserves below the seabed, and searching for new reserves is a very noisy business. Survey ships fire loud, low-frequency sounds from acoustic "guns" into the seabed. The echoes produced from each blast enable people to map the seabed and find where oil and gas may be hidden. These surveys can fire up to 40 guns every few seconds, for days or weeks at a time, and at any one time there can be 20–40 surveys going on around the world. Underwater, these blasts sound louder than standing next to a jet engine as it takes off! A seismic airgun blast is estimated to reach up to 260 underwater **decibels**. If you were standing close to a space shuttle as it launched, you would experience about 160 decibels (dB). Humans damage their hearing if they are exposed to 90 dB continuously, but we do not yet know the decibel level that causes long-term damage to marine life. The noise these guns produce is deafening to animals nearby, and as the sound waves can travel further than 4,000 km they affect the soundscape of large oceanic areas. Ocean exploration happens every day, raising noise pollution to dangerous levels and exposing marine life to levels of noise that would cause long-term damage to humans.

DECIBEL (DB)

A unit for sound, with a logarithmic scale. Every increase in 10 dB means the sound is 10 times louder. Human hearing is harmed by continuous sounds of 90 dB or above.

HOW DOES ALL THIS NOISE AFFECT MARINE ANIMALS?

Research has shown that animals may stop hunting for food or may leave protected areas because of noise pollution. Scientists often observe behavioral changes, such as species diving into deep water to escape noise or changing the amount of time they spend at the surface, alterations in the frequency of diving for food, and even changes in how vocal they are—all as a result of increasing noise in the soundscape.

Busy coral reefs are naturally noisy places, and new research shows that young fish use sounds to find the best reefs to live in [3]. But noise pollution can mask natural sounds, making it difficult for marine animals like fish (who make relatively quiet sounds) to hear each other, which interferes with their navigation. This can cause animals to become disorientated and vulnerable to predators, or even to become stranded on beaches as they try to escape underwater noise.

Studying the polluting effects of noise is difficult. We cannot give a whale a hearing test or ask a dolphin what it thinks about noisy gas and oil survey ships. Instead, we must study changes in noise levels, along with animal behavior, to find out how noise affects marine species. We can then use this information to build an idea of the impact of noise on our oceans.

Armed with this information, we might then work to make ships quieter, perhaps by redesigning their propellers and engines. We might also look at restricting how fast ships can travel and stop them from entering sensitive areas. In Boston, USA, scientists use hydrophones day and night in busy shipping lanes to listen for endangered right whales [4]. Their work is helping to reduce the number whales hit by boats.

Similar technologies are being developed for other species, and scientists are exploring how we can put hydrophones on swimming robots that roam the oceans all year, listening to the ocean soundscape and letting us know when it changes. Artificial intelligence systems are being used to teach these robots to detect calls belonging to certain whale species, enabling robots to survey our oceans much more quickly and accurately and to reach places that have never been surveyed before—including under the ice shelves of Antarctica![2]

[2] You can help! If you would like to help these swimming robots learn to recognize ocean sounds, visit Zooniverse (www.zooniverse.org). Here, you can learn to identify calls from various marine animals, then find them in recordings collected from all over the world.

Humans depend on the ocean for our way of life, but this way of life is causing harm to marine life. Understanding the effect anthropogenic noise has on marine life is increasingly important, and requires a deep understanding of the soundscapes. Reducing the amount of noise humans emit into the natural world is critical in our fight to protect wildlife all around us, and within our oceans.

FUNDING

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Experiment

Try out your own soundscape analysis:

Take 5 min to stand in your garden, local park or beach and listen to the sounds around you. Take a note of the time of day and maybe record what you can hear on a mobile phone. Then revisit the same place at different times of the day and re-record the soundscape. Make a list of what you can hear each time, and see if you can find any patterns. What time of day do the birds sing most? Can you hear any insects? Does traffic on the road mask specific sounds? How do sounds change throughout the day and from one day to the next?

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YOUNG REVIEWERS

CLASS 2A—SECONDARY SCHOOL LICEO SCIENTIFICO "DUCA DEGLI ABRUZZI", AGES: 15–16

We like English, problem solving, statistics, maths-science competitions and we eagerly joined in this project. We are quite sportive, quite creative, we love group activities, we all love music and the walls in our classroom are covered with posters of our favorite singers. We are tight-knit and we often go for a pizza. We are keen on sharing homemade desserts. We have a lot of fun dancing together! Our teachers say we are a very nice bunch of people.

ST OSCAR ROMERO CATHOLIC SCHOOL, AGES: 12–13

We are a group of Y8 and Y9 students at St Oscar Romero Catholic School in Worthing, UK. We love opportunities to extend our learning beyond the classroom, so it has been great to review scientific papers prior to publication!

AUTHORS

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Ellen L. White is a Ph.D. student at the School of Ocean and Earth Science, University of Southampton. Her main research theme are bioacoustics and marine soundscapes. Through the use of machine learning algorithms, she identifies interactions between marine mammal species and human activities to understand the affect anthropogenic activities are having on regional soundscapes and the animals that live there. Starting as a marine biologist she has a passion for ocean conservation and enjoys the challenge of the tech sector, learning new skills and creating new tools for analyzing big data sets, to extract ecological information which can help inform how best to protect our oceans. *elw1g13@soton.ac.uk

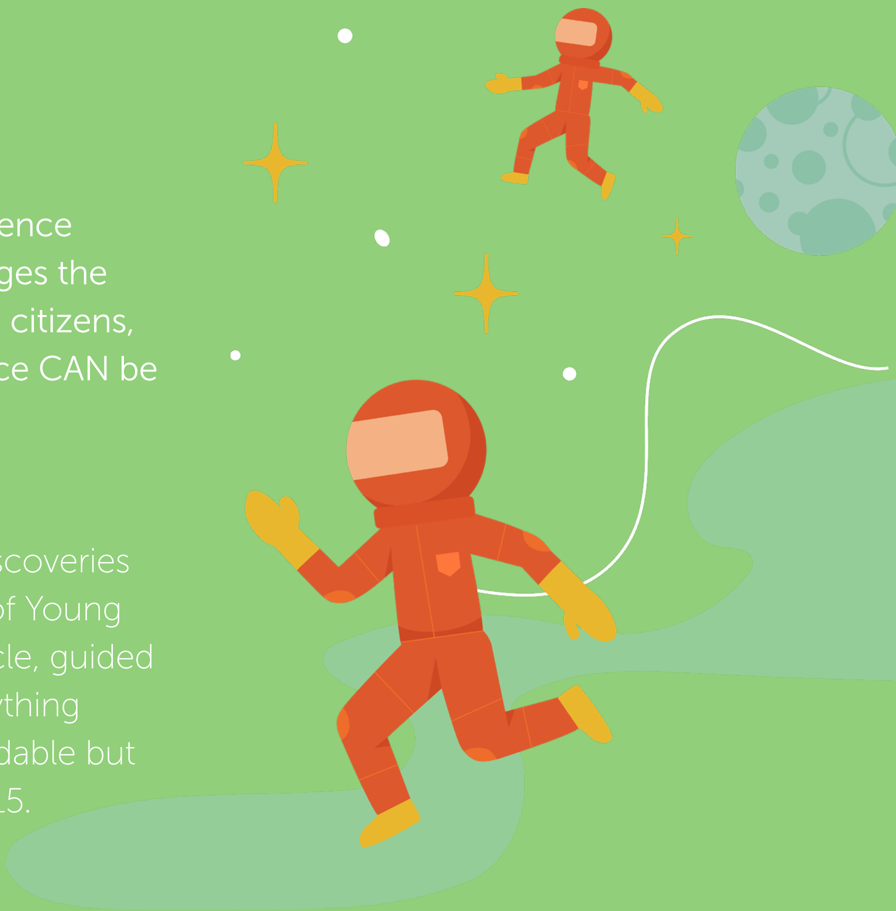
NIKHIL MISTRY

Dr. Nikhil Mistry is an underwater acoustics researcher, and his interests include Active/Passive Sonar, Bubble Acoustics and Signal processing. He is a passionate science educator and communicator, being a STEM ambassador since 2010, assisting in the university's Outreach roadshow, setting up a comedy club for researchers and facilitating a science cafe entitled "The Science Room."

PAUL R. WHITE

Prof. Paul R. White, is a professor of statistical signal processing at the Institute of Sound and Vibration (ISVR) at the University of Southampton, with research interests spanning the marine and terrestrial world. He currently leads projects in Carbon capture storage and is involved in research which spans theoretical acoustics, detection and classification of marine signals and methods for acoustic monitoring of species and soundscapes.

Frontiers for Young Minds



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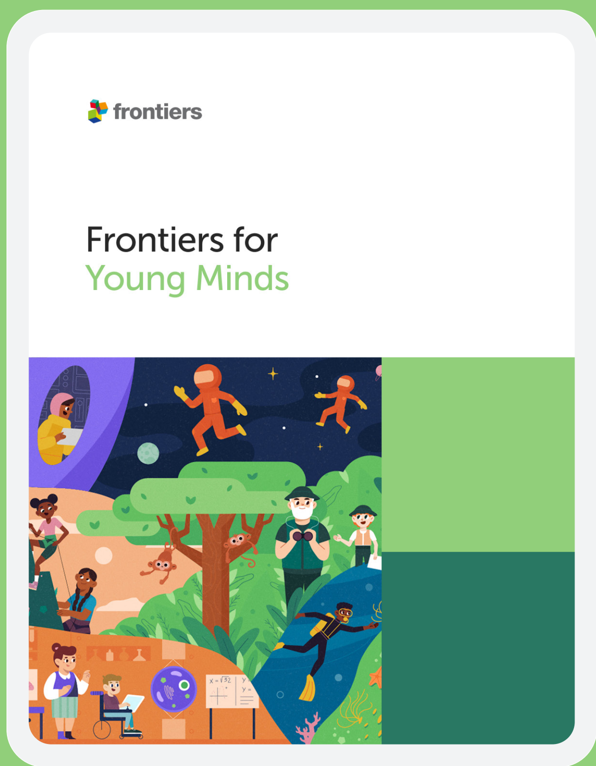

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