Noise May Be Music to Bionic Ears

BY MARK MCDONNELL and ROBERT MORSE

Bionic ear implants could be improved by introducing noise to mimic biological unpredictability.

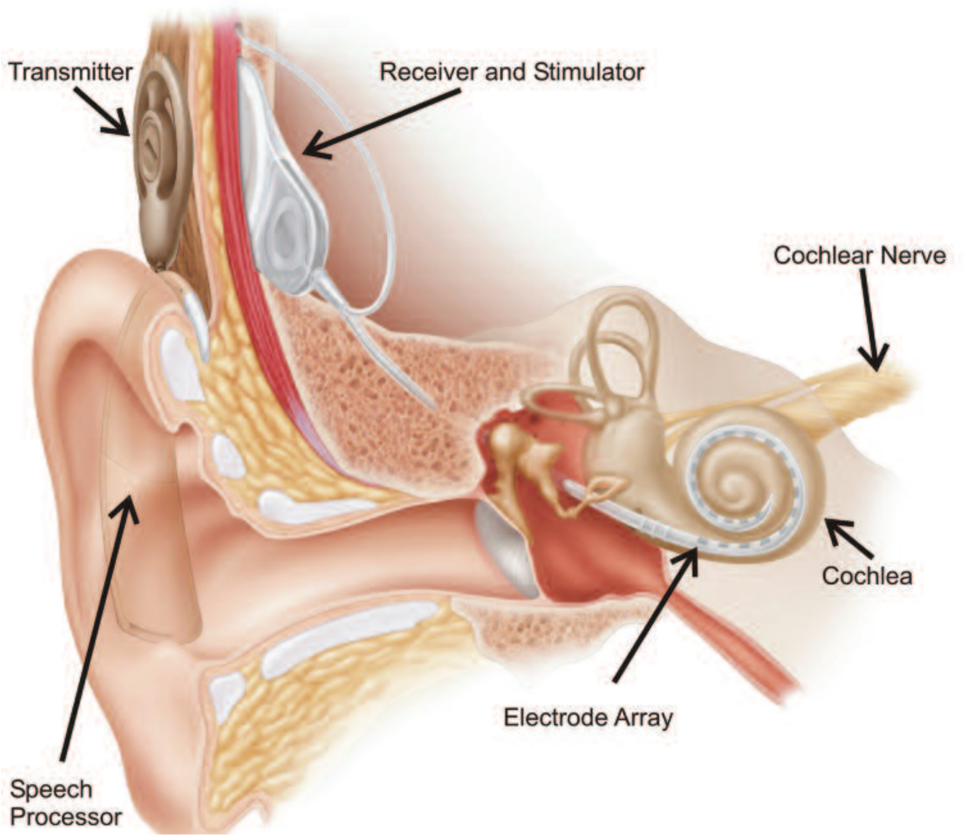
Cochlear implants, also known as bionic ears, are surgically implanted biomedical devices that can provide hearing to some deaf people. These implants can restore hearing when deafness has been caused by the loss of specialised hair cells in the inner ear. In a healthy ear these hair cells turn sound into electrical signals, and the information in these signals is then carried to the brain by the cochlear nerve.

The purpose of a cochlear implant is to mimic the behaviour of the missing hair cells. This is achieved by a microphone linked to an array of electrodes that are surgically implanted in the inner ear. Nowadays the operation is becoming commonplace – there are about 100,000 cochlear implants worldwide – and takes about 3–4 hours. Electrical current passing through the electrodes produces impulses in the cochlear nerve that the brain interprets as sounds.

The results achieved by cochlear implants are quite spectacular given that the electrode array provides only a small fraction of the full capability of the cochlear nerve to carry detailed information about sounds. Although the implants enable patients to converse without lip-reading, their ability to enjoy music or to understand speech against a background of voices, such as in a crowded restaurant, is more limited. This indicates that there is plenty of scope for improvement in cochlear implant technology.

One idea is to try to make the bionic ear stimulate the cochlear nerve in a way that more closely resembles stimulation in healthy ears. This might involve deliberately ensuring that a bionic ear's electrical pulses are unpredictable by using electrical "noise" that has properties like the static you might see when the TV is not tuned properly. While this seems highly counter-intuitive, there are strong theoretical reasons why this might be beneficial.

To understand how unpredictable stimulation of the cochlear nerve might be useful requires an explanation of how healthy hearing works and what changes when a cochlear implant is used.



Cross-section of the human head showing the components of a cochlear implant. The electrode array spirals around the cochlea and connects to a receiver and stimulator implanted in bone behind the ear. External to the head is the microphone, speech processor and transmitter. Image: Cochlear Ltd 2008

The external components (microphone, speech processor and transmitter) of a cochlear implant are worn behind the ear.

Image of Nucleus® Freedom™ BTE sound processor courtesy of Cochlear Limited 2008

How hearing works in healthy ears

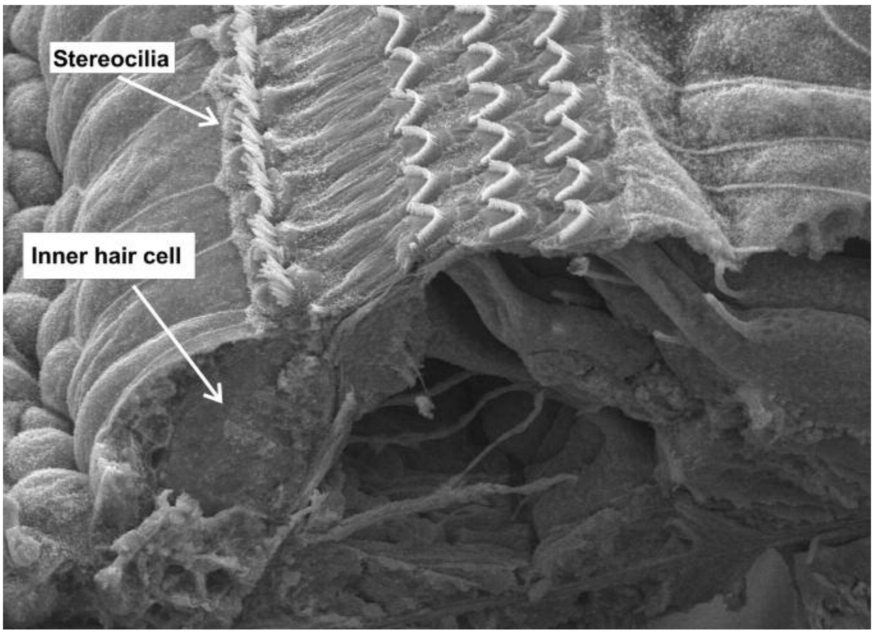
What we perceive as sound is caused by the vibration of air molecules. Just as a microphone turns these mechanical vibrations into an electrical signal in a wire, our ears need a way to convert mechanical energy into electrical activity so that the signals can be sent to the brain. This is achieved in a structure called the organ of Corti that contains the hair cells and is located within the cochlea (inner ear)..

The hair cells connect to about 30,000 sensory neurons, the fibres of which collectively form the cochlear nerve. These encode the pitch (frequency) and loudness (amplitude) of incoming sounds.

Just as white light contains the whole spectrum of light frequencies from red to violet, sounds typically contain a wide range of sound frequencies. For the brain to decode them, the ear needs to break up sounds into their constituent frequencies.

This is achieved by the remarkable mechanical properties of a structure inside the cochlea known as the basilar membrane, in which different regions are most sensitive to different frequencies. One end of the basilar membrane vibrates strongly to low frequency sounds while the other vibrates strongly to high frequency sounds.

The hair cells sit on top of the basilar membrane, and each connects to a number of fibres in the cochlear nerve. These hair cells are arranged down the length of the basilar membrane, and the end result is that some nerve fibres produce more nerve impulses in response to low-frequency sounds and others produce more in response to high-frequency sounds. The brain can decide what frequencies are present in a sound from which cochlear nerve fibres are active.



Scanning electron micrograph of a cross-section of the organ of Corti.

Photo: David Furness, Keele University, UK

The hair cells take their name from hair-like structures called stereocilia that project from one end. Movement of the basilar membrane causes these stereocilia to move, and the greater the deflection of the stereocilia the greater the electrical activity in the attached nerve fibres. Sounds that result in greater activity of the cochlear nerve over a period of time are perceived as being louder.

How Signal Level Is Coded into Electrical Signals

When recording sound in a modern sound studio, electronic devices connected to a microphone convert the sounds into electrical signals that can be processed by a computer. The sound level at any instant is represented electronically by one of a fixed number of digital voltages that is chosen by electronic comparison of the microphone output with a series of increasing "decision levels".

For studio recording, an electronic engineer would normally try and make the decision levels stable and predictable. An engineer would refer to any variability in the levels as "electrical noise" as the converted value might not accurately reflect the actual sound level.

With electronic technology it is possible to design circuits very precisely so that the levels of noise are very small. But how should sound level be coded when the sensor itself is naturally noisy?

This is the situation in biology, where the geometry and behaviour of the sensors is more variable, and increased precision would require too much energy use. Biological systems seem to take a different approach to coding: one that has probably evolved because of these constraints.

Experimental evidence suggests that each hair cell codes the sound level at any instant into electrical activity by a mechanism equivalent to an electronic digital sensor. However, unlike in electronics, if variability is ignored most of the hair cells' "decision levels" are the same!

If this were the case, all the neurons connected to a hair cell would behave identically, and all but one would be redundant because they would all send the same information. It would be like sending the same message down multiple telephone lines! Collectively they would code the sound level at any instant very poorly.

This is not actually the case though, because hair cells seem to take advantage of natural unpredictability in their decision levels. This "electrical noise" is so great that even in the absence of a sound each cochlear nerve fibre produces about 60 electrical impulses every second.

The unpredictable fluctuations in the "decision levels" mean that if the brain asks groups of neurons for a yes or no vote on whether a sound is at a particular level, it can use the number of yes votes to determine the sound level.

The internal components of a cochlear implant include the receiver, the stimulator and the electrode array. Image of Nucleus® Freedom™ cochlear implant courtesy of Cochlear Limited 2008

Without noise, all neurons would vote as a bloc, and the brain might as well only poll one of them. With it, each neuron could swing either way, but the higher the sound level at any instant, the more likely a yes vote.

Although the vote will be unpredictable and might occasionally miss the mark, this is more than compensated for by having a code with greater precision, provided there is not so much noise that the vote is nearly random. With the right amount of noise, substantially more information about sounds is sent to the brain than could be achieved without noise.

The effect by which noise can increase the amount of information coded by an array of sensors was first discovered in 2000 by Prof Nigel Stocks of the University of Warwick, and was termed suprathreshold stochastic resonance (SSR). Since then, our research has found that as long as there is the right combination of variability and redundancy, a noisy biological sensor that exploits SSR is almost as good as an ideal digital sensor.

We are currently working with colleagues at the University of South Australia's Institute for Telecommunications Research on understanding how our sense of hearing codes information about sounds in an efficient way. The idea is to study the brain using similar techniques to those used to code data and quantify "bit rates" in satellite and internet links. Understanding the role that unpredictability plays in normal hearing may be highly significant for future cochlear implants because the sources of noise known to exist in healthy ears are mostly missing in the deafened ear.

Modern Cochlear Implant Technology

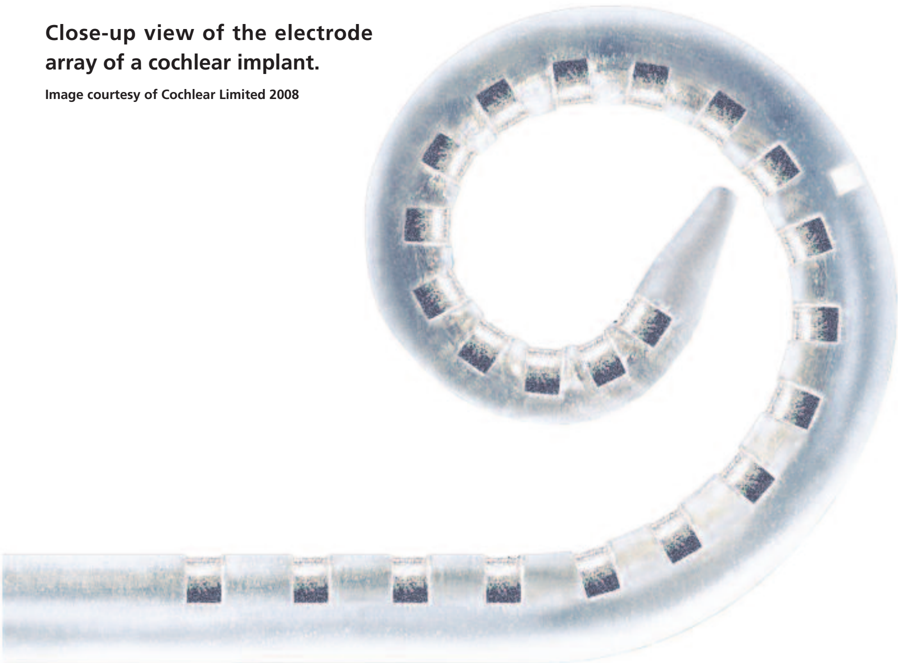
A modern cochlear implant consists of two separate parts. Externally, there is a microphone, sound processor and microphone that sit behind the ear like a hearing aid. The second part is the surgically implanted electrodes in the inner ear. Transmission of signals across the skull and the power for the internal electronics is provided by a radio-frequency link.

The signals picked up by the microphone are modified inside the speech processor into a form suitable for distribution in the electrode array. When activated, the electrodes in the array create electrical activity at different places in the cochlear nerve according to the frequencies present in the sound, thereby simulating the activity of a healthy ear to some extent.

Much of the pioneering work on cochlear implants was carried out by Prof Graeme Clarke, who went on to form

Close-up view of the electrode array of a cochlear implant.

Image courtesy of Cochlear Limited 2008



Cochlear Ltd after many years of research and much perseverance. The success of cochlear implants relies on a remarkable property of the brain known as plasticity.

Cochlear implants cannot stimulate the cochlear nerve in exactly the same way it is stimulated in the normal ear because an implant has only a few electrodes to stimulate the thousands of nerve fibres. However, plasticity enables the brains of implant patients to learn how to interpret the cochlear nerve activity induced by the implant.

People who lost their hearing relatively late in life can describe the differences between how they remember hearing, and how they hear when they first receive the implant. Typical descriptions are that it sounds like "Mickey Mouse" speech or "a radio not quite tuned in". Remarkably, as time goes by and the brain learns, sound perception becomes more like how it was remembered.

Ideally, cochlear implants would contain as many electrodes as there are nerve fibres in a healthy ear and would stimulate those fibres in exactly the same manner as healthy hair cells. This is impossible with current technology, and is likely to be highly impractical even with future technologies. Instead, efforts to improve performance need to focus on how to make the best of the limited number of electrodes that can be placed in the ear.

One way of doing this would be to try to artificially reintroduce the degree of controlled unpredictability that is present in the healthy ear but absent in the deafened ear. This unpredictability would enable nerve fibres that would otherwise be redundant to contribute to the coding of sound level.

Enhancing Cochlear Implants with Random Noise

A method for achieving this controlled randomness is being developed by us and our colleague, Nigel Stocks. Based on our earlier theoretical studies and Stocks' research into SSR, we are researching a method for adding "electrical noise" to the signals produced by cochlear implants that would compensate for the neural unpredictability that is missing in people with profound hearing loss.

The key to this working effectively is to ensure that the random fluctuations produced by each electrode leads to different variability in each nerve fibre. Otherwise, the problem of many neurons "voting as a bloc" would still happen.

There are some technical difficulties to overcome with this approach. However, we now believe that this problem has been partially solved using a method called stochastic beamforming.

An alternative proposal called conditioning has come from Jay Rubinstein of the University of Washington in Seattle. Rather than producing unpredictability by randomising the electrical current produced from an electrode, the idea is to achieve the same result by stimulating the electrodes with regular low-level pulses of current at a very fast rate. The unresolved question with this approach is how to control the level of unpredictability that is crucial for SSR.

A third alternative might be pharmaceutical rather than technological. Certain drugs are known to increase the unpredictability of neurons, and it might be possible to design a drug that can be suitably introduced into the cochlea.

Regardless of which approach proves most useful in practice, it seems that researchers agree that it is desirable for the response of the cochlear nerve to be made more like that in a healthy ear. Controlled unpredictability may one day bring the joys of listening to music to many more bionic ear patients.

The fantastic success of bionic ears in restoring hearing shows that even a crude way of replicating biological senses can have substantial benefits, and this is now inspiring researchers to work on even more ambitious goals, such as the bionic eye program recently underway in Australia, and the possibility of spinal cord repair. Perhaps future prosthetics that restore sight or other lost function will rely on the same mixture of brain plasticity, science and inspired biomedical engineering that has led to the bionic ear.

Mark McDonnell is an ARC Discovery project-funded postdoctoral research fellow at the University of South Australia's Institute for Telecommunications Research. Robert Morse is a Lecturer in Audiology in the School of Life & Health Sciences at Aston University, UK.