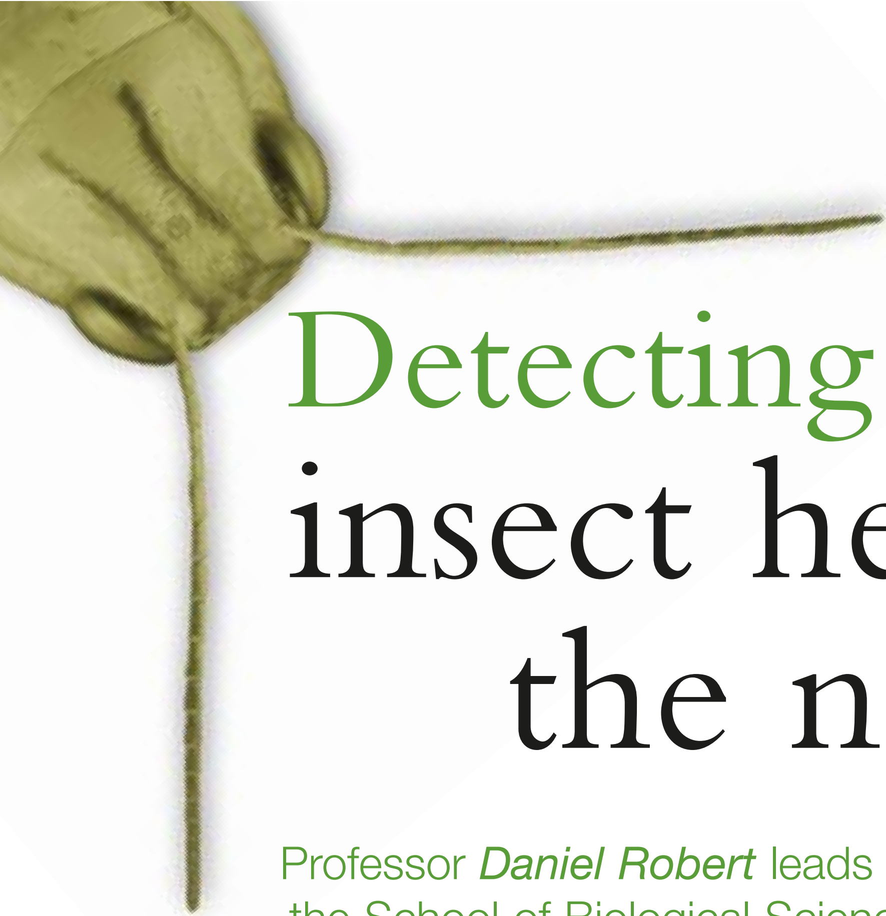


Detecting the limit: insect hearing at the nanoscale

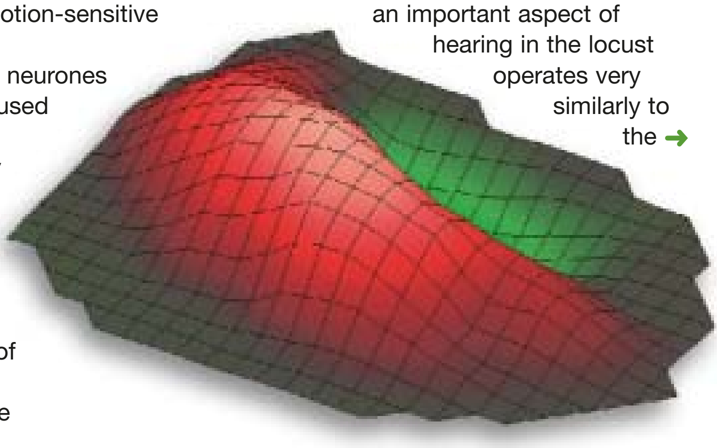
Professor ***Daniel Robert*** leads the Bionanoscience Group, in the School of Biological Sciences. There they use insects as model systems to help understand the fundamentals of hearing.

Living organisms are fascinating assemblies of elementary nanoscale building blocks, ie atoms and molecules, of astonishing complexity and sophistication. These building blocks combine to form the elegant sensors found in hearing organs. Studying these biological systems could generate the knowledge necessary for the design and construction of bio-inspired analogues, such as miniature directional microphones or instruments capable of ‘seeing’ atoms.

> These vibrations are at the theoretical limit of detection

In the auditory systems of humans, mammals, frogs and some reptiles, the physical structures responsible for hearing are tiny hair ‘bundles’, located at the top of hair cells. Detection of a sound occurs when the hair bundles are deflected by sound waves. Quite remarkably, some of these hair cells are not only very sensitive sensors, they also generate their own vibrations in response to sound, resulting in enhanced auditory sensitivity and a sharpening of frequency detection. This process is known as *active* audition. The exact cellular and molecular mechanisms supporting active audition are still unknown and remain a challenge in the field of auditory neuroscience. In particular, the question of how the hair ‘knows’ when and how much to activate itself remains outstanding, and bears relevance to both fundamental and clinical auditory research.

In recent years, work has established that insects use active audition with similar effects to that in mammals, but by relying on fundamentally different mechanisms. For example, hearing in the fruit fly is assisted by the action and reaction of motion-sensitive sensory cells – mechanoreceptor neurones – to vibrations caused by sound. Such neurones in many insects are capable of detecting vibrations that are theoretically at the very limits of motion detection. Despite this, these sophisticated biological-mechanical systems can be amazingly robust and reliable. Quite surprisingly, it has been demonstrated that these neurones can be motion *generators* as well as motion sensors, merging two fundamental biological functions into one cellular entity. So, for example, the female fruit fly’s auditory neurones not only receive sounds, but they also generate motions that drive the antenna and tune it to biologically relevant sounds, such as the buzz made when a male fruit fly ‘sings’.



Some of the latest work in the Bionanoscience Group has investigated the remarkable properties of the ears found in locusts and moths. Experiments by Dr James Windmill have led to the discovery that an important aspect of hearing in the locust operates very similarly to the ➜

The Large Yellow Underwing moth has some of the simplest ears known

➜ inner ear of humans. In the locust, the method for analysing sound frequencies relies on nanoscale waves that travel across the locust's eardrum – the tympanal membrane – much like the waves that propagate along the cochlea in the inner ear of humans. The process results in the focusing of energy from different frequencies to groups of mechanoreceptor neurones attached at different places across the membrane. The locust's ear therefore combines in one elegant structure the functions of both sound reception and frequency analysis.

Further research, conducted on the Large Yellow Underwing moth, has also revealed remarkable nanoscale biomechanical processing capabilities. The moth's ears typically have only two mechanoreceptor cells, making them some of the simplest ears known to exist. However, many moths can hear large frequency ranges, from 20 kHz to over 80 kHz, in order to listen out for the echolocation calls of their predator, the bat. Dr Windmill's investigations have shown that the faintest sounds that moths can hear cause motions of the tympanal membrane of about 50 picometres (one picometre is a thousandth of a nanometre, which is a billionth of a metre). This extreme sensitivity is the equivalent of the Clifton Suspension Bridge moving up and down a fraction of a millimetre. Any windy day or passing vehicle will have a much larger effect than that.

These biological hearing systems are remarkable designs that have evolved over millions of years by outsmarting predators. By understanding how insect ears combine robustness with extreme sensitivity, future designs of instruments such as the atomic force microscope could be revolutionised. This 'microscope' uses a micro-sized arm, rather like that of an old-fashioned record player, with a sharp tip (the needle) that is, ideally, only one atom wide. It provides pictures of atoms on or in surfaces by measuring the tiny forces around the atoms. It is used at Bristol, for example, to observe processes in DNA.
Researchers in the Bionanoscience Group have shown that insects sense the world around them in the same way – by measuring tiny forces. An appreciation of insect hearing may thus contribute to the development of new analytical devices, across a range of disciplines such as medical, environmental and material science. ■

www.bio.bris.ac.uk

Professor Robert's research at Bristol is funded by the Interdisciplinary Research Collaboration in Nanotechnology, the Biotechnology and Biological Sciences Research Council and the Royal Society.

Image captions:

Above: A fruit fly head, with hearing organs to the front. On the left you can see one of the hearing antennae, approximately 300 microns long.

Left: The inside of a moth's ear. The mechanosensory neurones (end shown in pink) stretch up to attach to the ear's tympanal membrane. The motion of the membrane due to sound causes the neurones to be pulled up and down, which in turn triggers them to produce electrical signals to the nervous system.

Far top left: The locust, *Schistocerca gregaria*, used in the investigations here at Bristol.

Far bottom left: A 3D view of how a wave travels across the locust's tympanal membrane. This image shows a snapshot in time of the membrane's motion, as a wave moves from left to right. This image is greatly exaggerated so that we can see the waves; the membrane is actually 1.5 millimetres across, yet the waves are only a few nanometres high.

New Nanotechnology Centre

The past few years have seen an enormous expansion in our ability to manipulate the structures and properties of complex materials at the atomic level. Recognition of the excellence of the work being done in this area at the University of Bristol has resulted in an Interdisciplinary Research Collaboration in Nanotechnology being jointly awarded to the universities of Bristol, Cambridge and University College London by the joint research councils, the Ministry of Defence and the Department of Trade and Industry. It is funded with £10 million for six years and has already attracted substantial further funding.