Fishing for function in noise

James J. Collins

Stochastic resonance increases the ability of some nonlinear systems to detect weak signals. Paddlefish are now shown to use stochastic resonance to locate and capture prey, implicating this phenomenon in animal behaviour.

In everyday life, noise is usually viewed as being detrimental to detecting signals and transmitting information. We tune out static noise from our radios, pay extra money for cellular phones with clear reception, and move away from a loud pneumatic drill when trying to have a conversation. Engineers spend considerable time and effort designing noise filters, which are common in many consumer goods and scientific instruments. As one of my colleagues remarked, "I have filters in every piece of equipment in my laboratory, including the coffee pot". But on page 291 of this issue, Russell, Wilkens and Moss[1] challenge the idea that noise is always harmful. Instead they show that, in some cases, noise can be beneficial and that it may improve the functional behaviour of an animal.

This work is based on the phenomenon of stochastic resonance, originally proposed by physicists in the early 1980s in the context of global climate modelling[2,3]. Stochastic resonance is an effect by which the ability of certain nonlinear systems to detect and transmit weak signals can be enhanced by the presence of a certain level of noise. This effect was limited to physical systems until 1991, when a report in *Physical Review Letters*[4] described the discovery of stochastic resonance in sensory neurons.

John Maddox, then editor of *Nature*, featured this study in a News and Views article[5] entitled "Towards the brain-computer's code?". Maddox's article brought stochastic resonance to the attention of the broader scientific community, highlighting the possible benefits of noise in nonlinear systems — in particular, in biological systems. Since then, stochastic-resonance-type effects have been demonstrated in a range of such systems. These include crayfish mechanoreceptors[6] (which detect mechanical signals such as water movement), the cricket cercal sensory system[7] (which detects air disturbances) and human muscle spindles[8] (which detect muscle stretch). This work[4] laid the foundation for the development of noise-based sensory prosthetics[9] and mechanical ventilators[10], both of which could have considerable clinical implications.

Despite such advances, the influence of stochastic resonance has been limited in the biological community. This is partly due to scepticism associated with this counterintuitive phenomenon, and concerns about its unfulfilled promise. Some have speculated that neurophysiological sensory systems may have evolved to take advantage of stochastic resonance as a means for enhancing performance and functionality[6]. This is an attractive hypothesis, but one with little evidence — at least until now.

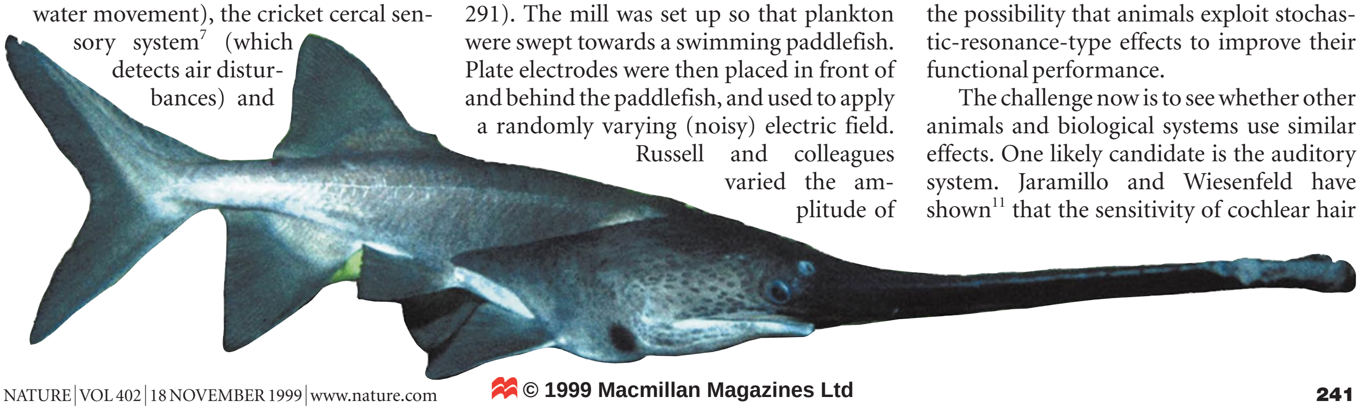
Most previous work on stochastic resonance in biological systems has been limited to theoretical and experimental demonstrations that the phenomenon can, indeed, occur in a given system. Although valuable as a first step, such work does not allow us to see whether noise-enhanced signal detection has any functional benefit for the system, animal or subject under study. Russell and colleagues[1] have now overcome this shortcoming with a clever experiment designed to examine the feeding behaviour of paddlefish (*Polyodon spathula*, pictured below).

Paddlefish use passive electroreceptors to detect electrical signals from their prey, minute zooplankton such as *Daphnia*. The zooplankton generate such signals from nerve excitations, which are used to move their swimming and feeding appendages. Russell *et al.* hypothesized that certain levels of externally applied electrical noise could enhance the ability of paddlefish to locate and capture plankton. To test this hypothesis, they constructed a swim mill with a recirculating stream of water (see Fig. 1a on page 291). The mill was set up so that plankton were swept towards a swimming paddlefish. Plate electrodes were then placed in front of and behind the paddlefish, and used to apply a randomly varying (noisy) electric field. Russell and colleagues varied the amplitude of the field and measured the spatial distribution of strike locations (where the paddlefish caught the plankton) as a function of field amplitude. If only nearby plankton were located and captured then the distribution of strike locations was narrow; if more distant prey were detected and eaten, the distribution was broader.

The authors found that when they applied an intermediate level of noise, the width of the strike-location distribution for each of the four paddlefish tested was considerably increased compared with a zero-field control. Moreover, at this 'optimal' noise level, the capture rates for two of the paddlefish increased by about 50% on average. For the two other fish, the capture rates for the optimal-noise and control conditions were similar. In contrast, when Russell *et al.* applied high levels of noise, the distribution of strike locations became compressed and the capture rate diminished. In fact, at the highest noise levels, the paddlefish almost completely stopped feeding. These findings are consistent with stochastic resonance, and indicate that the ability of paddlefish to locate and capture prey can be improved by the presence of some noise. This is the first demonstration that noise-enhanced sensory dynamics can lead to improved functional behaviour — in this case, feeding.

What is a natural noise source, if any, for paddlefish? Russell and colleagues provide evidence in support of one possibility — the plankton themselves. They show that swarms of plankton give off electrical signals that fluctuate randomly. These population-based signals could constitute a source of background noise that increases the sensitivity of paddlefish electroreceptors to the electrical signals given off by individual plankton. Such dynamics could enable paddlefish to detect more distant prey. This work raises the possibility that animals exploit stochastic-resonance-type effects to improve their functional performance.

The challenge now is to see whether other animals and biological systems use similar effects. One likely candidate is the auditory system. Jaramillo and Wiesenfeld have shown[11] that the sensitivity of cochlear hair



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cells in frogs is enhanced by the natural Brownian motion of those hair cells. These authors argue that the random fluctuations associated with the hair-cell Brownian motion is essential for the transduction of weak signals in the cochlea. So biological systems may have evolved not to ignore noise in their environments, but to take advantage of it. ■

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Materials science

Open season for solid frameworks

Michael J. Zaworotko

Zeolites are inorganic solids whose crystal structures are perforated by millions of tiny pores and channels that allow the movement of ions and water molecules. These 'molecular sieves' have found widespread applications in industry for catalysis and for separating materials, such as in oil refining[1]. In the home, zeolites are found in water softeners where sodium ions in the pores are easily exchanged with calcium and magnesium ions dissolved in hard water. Until four years ago, such microporosity was thought to be limited to a select group of silicate- or phosphate-based zeolites, with a few notable exceptions. A novel metal–organic framework, reported by Li *et al.*[2] on page 276 of this issue, offers a new way to design microporous structures from first principles.

Many of the new 'zeolite analogues' are based upon metal and organic linkers, and are known as coordination polymers. The first generation of coordination polymers that were made by crystal-engineering strategies (as opposed to chance) had various problems. Some synthetic compounds failed to support a vacuum because of interpenetration by two or more independent networks[3], whereas others irreversibly collapsed in the absence of guest molecules[4]. Subsequent studies produced a second generation of 'open frameworks' that are more closely related to zeolites as they are robust enough to survive complete loss of guest molecules and they can reversibly exchange small volatile molecules. Such structures can either be purely organic and sustained by hydrogen bonds[5] or they can be based upon coordination-polymer frameworks[6]. It is reasonable to claim that the new compound designed by Li *et al.*[2] — $Zn_4O(BDC)_3$, where BDC is benzenedicarboxylate — is the prototype for a third generation of open frameworks that offer a number of advantages over traditional zeolites.

Ultimately, the most important consequence of the new work is likely to be our increased ability to engineer microporous structures and tailor cavities and channels in a precise manner. From this perspective, $Zn_4O(BDC)_3$ is a rare example of a compound that is created in an entirely predictable way based upon the symmetry of its components. In a sense, we are now building frameworks from predefined building blocks[7], a molecular analogue of Lego or Meccano. Furthermore, $Zn_4O(BDC)_3$ confirms that a full range of chemical building blocks can be used to make microporous materials, including purely organic and metal–organic solids. Here, the Zn_4O core acts as a node, or vertex, in an octahedral framework[8,9]. At first glance this might appear counterintuitive, as the Zn_4O core is a tetrahedron (Fig. 1a). However, it generates an octahedral framework because it is linked to neighbouring Zn_4O nodes by its edges rather than its vertices.

In terms of its properties, $Zn_4O(BDC)_3$ is a relatively simple and inexpensive material to prepare and is remarkably stable after loss or exchange of guest molecules, remaining crystalline at temperatures above 300 °C. The key feature that makes $Zn_4O(BDC)_3$ special is that it exhibits a degree of porosity that is unprecedented in a crystalline solid. As shown in Fig. 1b, the octahedral framework has large pores and cavities that can accommodate and release organic molecules such as chlorobenzene and dimethylformamide. Calculations and experimental data indicate that about 60% of the structure is accessible to guest molecules, which is double the volume available in most crystalline zeolites[10].

The implications of this work are far reaching for at least two reasons. First, although $Zn_4O(BDC)_3$ does not contain pores and cavities that exceed an effective diameter of 10 Å (1 Å = 0.1 nm), neither do zeolites[11]. That said, 15–30-Å channels have already been observed in coordination polymers[12] and if such dimensions can be incorporated into structures such as $Zn_4O(BDC)_3$ then we would in effect be dealing with a new class of 'mesoporous' structures that are both crystalline and designed from first principles.

There is much demand for large-pore structures that can contain and catalyse reactions involving large molecules or clusters of smaller molecules. Interesting things are expected to happen inside the 15–30-Å domain because it is large enough to contain aggregates of medium-sized molecules but small enough to constrain and control them in a manner that could mimic, at least in a primitive sense, what enzymes do to substrates. Furthermore, the molecules would be in an environment that is intermediate between the solid state, where there is long-range order, and the liquid phase, where there is only short-range order. This is uncharted territory for crystalline solids.

Second, chemical modification of pores and cavities should be much easier. Desir-

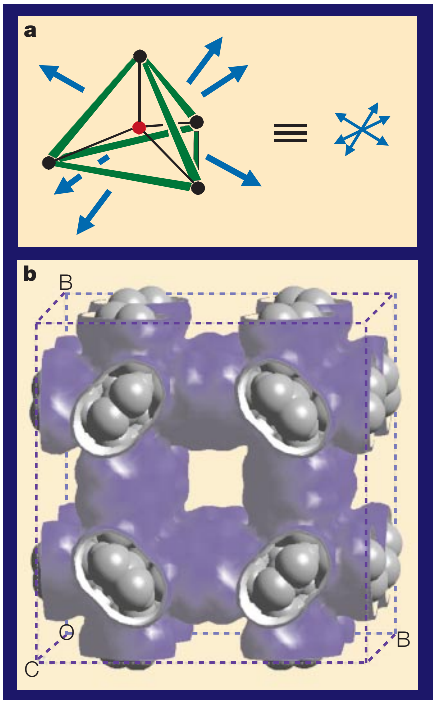

Figure 1 **A microporous material designed from first principles. The compound $Zn_4O(BDC)_3$ designed by Li *et al.*[2] is twice as porous as most zeolites.** a, **ZnO is the tetrahedral (four-sided) core of $Zn_4O(BDC)_3$, which can generate an octahedral framework (with six-fold coordination) because it is linked to neighbouring cores by its edges rather than by its vertices or faces. (Zinc, black atoms; oxygen, red atoms).** b, **A portion of the crystal structure of $Zn_4O(BDC)_3$. The framework is in grey and the surfaces are blue. The octahedral framework is highly accessible to guest molecules and remains stable after release or exchange of molecules.**