Published in *Physics World* **15,** 20-21 (2002).

Stochastic Resonance in the Head

Random noise may be of positive benefit to information processing in the human brain. This is the implication of results obtained by Toshio Mori and Shoichi Kai of Kyushu University, reported in the 27 May 2002 issue of *Physical Review Letters*. They have shown that the visual processing region of the cortex responds better to an external periodic stimulus when external noise is also applied – apparently representing yet another example of the seemingly obiquitous phenomenon of stochastic resonance, and one of the most interesting biological examples to date.

The notion of stochastic resonance (SR) was originally introduced in connection with the Earth's ice-age cycle, in an attempt to explain how a tiny periodic variation in the amount of radiation reaching the surface (the Milankovich cycle, with a period of about 100,000 years) could trigger the huge climatic changes that are observed. In stochastic resonance, a weak periodic signal in a noisy system can be enhanced by adding extra noise – an astonishing effect that was identified almost simultaneously about 20 years ago by Roberto Benzi and colleagues in Rome, and by Katy Nicolis in Brussels. Even more remarkably, there are many cases where it is not only the signal that is enhanced by noise, but also the signal/noise ratio.

Although SR seemed very mysterious at first, and there were even suggestions that it violated the Second Law of Thermodynamics, it was accounted for in 1990 by Mark Dykman, who was then in Kiev (now in Michigan State University). He used classical linear response theory to demonstrate that SR is to be anticipated in any noisy system whose complex susceptibilty is strongly noise-dependent. In practice there are numerous such systems, one of the commonest kinds being the class of two-state systems or oscillators in which there are two potential wells. In cases of this latter kind, the physical origin of the SR is intuitively obvious: in the presence of noise, a weak periodic signal can induce coherent hopping between two well-separated states, i.e. the noise produces much larger excursions than occur without the hopping, thus amplifying the signal. There is clearly an optimal noise intensity. With insufficient noise, no hopping takes place at all; but with too much noise the hopping occurs randomly, independent of the periodic signal. So, with increasing noise intensity, the signal at the output rises, passes through a maximum, and then decreases again – providing the now well known signature of SR. But, as Dykman showed, SR is by no means restricted to two-state systems but arises far more generally.

Dykman's picture immediately set SR in context within statistical physics. But, although the phenomenon became instantly less mysterious, it remained no less remarkable, and examples of SR have continued to multiply. Quite apart from the ice-age cycle, the effect is now known to occur in systems as diverse as lasers, electronic circuits, sensory neurons and financial markets. Of course, the fact that it arises in biological systems raises the interesting question of whether they have evolved like that in order to exploit SR to good effect.

SR has been well demonstrated in the peripheral nervous system and in sensory signal transduction, for example by Frank Moss and colleagues in St Louis who found clear evidence of SR in crayfish mechanoreceptor hairs, and in the main sensory organ of a paddlefish. It has been conjectured that SR may also arise in the brain. But the hypothesis has been peculiarly difficult to verify because of the difficulty of distinguishing between SR in the brain and SR in the sensory organs through which the signal and added noise must pass in order to reach the brain.

Mori and Kai have evaded this difficulty by exploiting the particular way in which the eyes are "wired up" to the brain. Their experiment was arranged as shown in Fig 1. It used the subject's two eyes in different roles: a periodic light signal was applied to one eyelid, and a random optical signal (noise) to the other eyelid, both eyes being kept shut. Thus, the noise and signal did not interact until they reached the optic chiasma and visual cortex. Hence there was no possibility of complications caused by SR within the eyes themselves. A periodic visual signal of sufficient strength, and in the right frequency range, is known to induce coherent, synchronized, firing of neurons in sympathy with the signal over a large area of the brain. Mori and Kai ensured that, in the absence of noise, their signal stimulus was below the threshold needed for this effect to occur. The brain waves were detected with standard electroencephalograph (EEG) electrodes on the skin. They found that a stronger, synchronized, response to the signal could be stimulated by the noise, and that it was optimized for a particular noise intensity, as shown in Fig. 2.

Fig. 2 looks just like a classical SR plot. It was evidently much the same for the five subjects measured, and it is very similar in form to numerous results obtained from diverse other SR systems. So what are we to conclude? Well, definitely that SR can occur in the human brain, in itself an interesting and important result. But the real $64k questions are whether SR also occurs naturally, and whether the brain exploits this remarkable phenomenon in order to enhance its normal information processing activities. These are far harder questions to tackle and doubtless will be the subject of future investigations.

Figures

1. Experimental arrangement used by Mori and Kai. Noise entering the left eye, and the periodic signal entering the right eye, induce separate optical neural signals that only come together deep inside the brain. [**Please lift Fig 1 of T. Mori and S. Kai, *Phys. Rev. Lett.* 88, 218101 (2002)**].

2. Response of the brain to the periodic signal, as a function of noise intensity Q_N. The different symbols refer to particular subjects and the curve is a guide to the eye. [**Please lift Fig 5 of T. Mori and S. Kai, *Phys. Rev. Lett.* 88, 218101 (2002)**].

Peter V.E. McClintock, Lancaster University, 26 May 2002.