although the ocean is indeed partly driven by such buoyancy forces (of order 1 TW), they cannot drive the mixing because the ocean is an inefficient heat engine; that is, differences in temperature are not transformed effectively into work done in the form of moving water masses.

Instead, say Munk and Wunsch, the prime candidates appear to be more mechanical: tidal dissipation, largely powered by the Moon, and wind driving (Fig. 1). Tidal dissipation has usually been assumed to occur predominantly in bottom boundary layers on shallow ocean shelves, because dissipation varies as the cube of the water speed, and ocean tidal velocities tend to vary inversely with ocean depth. Enough dissipation appears to be left over, however, in the form of internal tides (about which little is known) to provide about 1 TW of power, some in the form of turbulence away from the ocean floor, but most as turbulent patches through scattering by topography. The remainder of the energy is input directly as work done by wind at the ocean surface (another 1.2 TW; see Fig. 1).

So, although with many uncertainties, energy sources for deep-ocean mixing are fairly clear. The variety of mechanisms involved are much less so. Boundary mixing — preferentially high mixing due to turbulence in bottom and side boundary layers — has long been a candidate, and theories relating such mixing to effective internal ocean diffusivities exist. But there are few direct measurements of these processes and caution is necessary in extrapolating from what little we do know. In a manner that we do not understand, there are regions in which inferred diffusivities are several orders of magnitude higher than background[6], and they are usually located over steep structures on the ocean floor. This is in line with beliefs that tidal energy spreads from ridges and other topographic features — and there is a lot of topography in the ocean (over half a million seamounts in the Pacific alone).

Almost everything in “Abyssal recipes II” remains uncertain: oceanographers have no way to survey large tracts of the ocean interior; the possible range of both processes and locations is huge; and estimates of the power generation necessary have wide error bars. We need modelling work to see how the processes can add up. Such modelling has to be both process-oriented (to explore the various possibilities) and heavily numerical, including some or all of the processes — for example, no general circulation model I am aware of contains tidal mixing.

To cap it all nicely, Munk and Wunsch[2] note in passing: “To many readers, the proposal that the Moon plays a major role in the general [ocean] circulation will border on the lunatic”. Maybe, maybe not. It’s a lovely concept. ☐

Peter Killworth is at the Southampton Oceanography Centre, Empress Dock, Southampton SO14 3ZH, UK.
e-mail: P.Killworth@soc.soton.ac.uk

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Auditory perception

Sounds in a virtual world

Malcolm N. Semple

Sounds delivered through headphones can be made to seem as though they originate from sources outside the head — a compelling illusion known as virtual auditory space. Although current implementations are far from perfect, progress has been encouraging[1] and practical applications could include enhancing the information content of virtual environments such as military simulations or computer games. Virtual auditory space also allows auditory researchers to control stimuli very precisely and to investigate stimuli, such as moving sounds, that are difficult to generate using free-field speakers.

On page 747 of this issue, Kulkarni and Colburn[2] provide new insight into the factors that underlie the externalized perception of a sound source. In principle, for a listener to perceive virtual auditory space as real, the normal cues for directional hearing must be simulated accurately through headphones. What are the cues? There has been a long history of investigation into how we detect where a sound is coming from[3], dating back to the work of Lord Rayleigh in the last century. Psychoacoustic and physiological studies emphasized two main cues for detecting the direction of a sound source with both ears: the time delay between the sound reaching one ear and the other; and the difference in sound level at the two ears (Fig. 1, overleaf). These ‘binaural difference cues’ are computed within the brain after the information from each ear converges there.

Over the past decade there has been a growing awareness that the characteristics of the external ears also contribute to our perception of where a sound is coming from. ‘Spectral cues’ are generated because the outer part of the ear, the cone-shaped pinna, applies a filter function — the ‘head-related

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100 YEARS AGO

The proposed application of electrical power for mounting plays at Drury Lane, on the lines advocated by Mr. Edwin O. Sachs, has now taken a tangible form in the completion of the first section of the stage installation in time for the impending pantomime. Mr Sachs’ present work refers principally to the stage floor and its movability in sections above and below the footlights. The total area now already movable by mechanical power exceeds 1200 square feet. The electrical appliances just completed take the form of so-called “bridges,” each working independently. ... They can travel about 20 feet vertically.

From *Nature* 29 December 1898.

50 YEARS AGO

J. Bardeen and W. H. Brattain, of the Bell Telephone Laboratories, in the course of general investigation, initiated and directed by W. H. Shockley, on the properties of semiconductors, have developed a new three-element electronic device, called by them a ‘transistor’ (transfer-resistor) or ‘semi-conductor triode’. This can be employed as an amplifier or oscillator and can replace the vacuum triode in most electronic circuits. The device, which consists of a metal cylinder, about an inch long and of the thickness of a pencil, containing the germanium and its three electrodes, was demonstrated with great success recently at a Press conference in New York. ... In place of the single ‘cat’s whisker’ of the crystal rectifier, two fine wires (both tungsten and phosphor-bronze have been used) make contact with the upper surface of the germanium block. These electrodes, the emitter and collector, are about 0.005–0.025 cm apart. The third electrode, which is a large-area low resistance contact, makes contact with the base of the block. ... Amplifications up to 100 times, that is to say, a gain of 20 decibels, have been obtained. The transistor uses less power than a vacuum tube, has an output of 25 milliwatts and can operate at frequencies up to 10 megacycles per second. ... The transistor is not yet in production, but its simplicity, small size, performance, long life, and probably low cost when mass-produced, should find many applications in all forms of electronic equipment.

From *Nature* 25 December 1948.

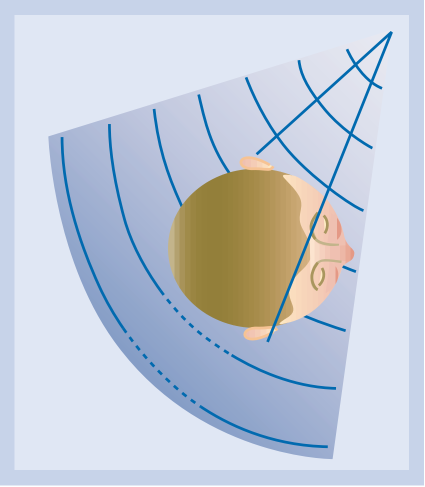

Figure 1 **The two ears, like the eyes, capture the world from slightly different perspectives. When a sound is displaced to one side of the head it arrives earlier at the near ear, leading to a time difference between the two ears. If the wavelength is short relative to the size of the head, reflection and refraction will attenuate the signal en route to the far ear, leading to a difference in the level between the ears.**

transfer function' (HRTF) — to the sound, shaping its amplitude and phase spectra (Fig. 2). There is now a general consensus that these external-ear spectral cues provide information about the location of a sound source in the vertical plane (or 'elevation')[4], and that the binaural difference cues provide a basis for discerning the horizontal angle (or 'azimuth') of the sound. Although the effects of the external ear are commonly described as being 'monaural spectral cues', the cue is not exclusively from one ear because the spectral notches shape each ear's input to the neurons that process signals from both ears.

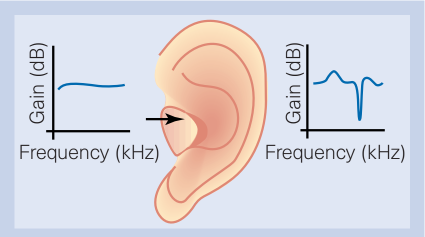

Figure 2 **Filtering of sound by the external ear. As sound is funnelled to the ear canal, it is subjected to a frequency-dependent filtering that modifies the phase and amplitude spectra. This filtering is known as the 'head-related transfer function' (HRTF), and Kulkarni and Colburn[2] measured it by inserting a microphone probe tube deep into the ear canal, to sample signals near the eardrum. They then compared these signals with signals recorded near the entrance to the ear. The measurement was repeated for sounds coming from a range of locations.**

The impression of a sound with direction can be generated through stereophonic headphones by incorporating differences in the timing and intensity of the signals at the two ears. But these auditory images are typically confined within the head. Externalized images can be elicited only by carefully compensating for any spectral coloration generated by the headphones, and by applying a filter function to compensate for the normal HRTF. Hartmann and Wittenberg[5] were the first to investigate the factors that are important for externalizing the acoustic image in a controlled way, and they found that externalization requires realistic spectral profiles in each ear — that is, the sound experienced at the eardrum should reproduce the sound that would occur naturally. Because there is considerable variability in the size and shape of the human pinna, such a realistic virtual space image requires that the listener's own HRTF is measured[6]. In fact, when people try to listen via the filtering of another person's ears, their ability to distinguish where a sound is coming from suffers markedly[7]. Moreover, there is evidence that in the normal course of repositioning the headphones, the HRTF may be shifted considerably.

These are serious obstacles to the widespread use of virtual auditory space, because measuring the HRTF is time-consuming and exacting. One hope is that by learning more about which details of the HRTF are responsible for externalizing the acoustic image, we may be able to avoid having to include every last detail of the HRTF in the calculations. Kulkarni and Colburn[2] have now made considerable progress towards this goal. Using an open-earphone technique that allows sound to be presented either from a real free-field source or as a virtual image, the authors asked listeners to discriminate between real and virtual sounds. Usually, virtual sounds are given through headphones, which must then be removed for presentation of real sounds. Instead, Kulkarni and Colburn delivered the virtual sounds into the ear canal through small tubes so that, without removing the tube-phones, sounds originating from an external speaker could enter the ear unimpeded. They could then immediately compare how accurately a virtual sound reproduced the real sound that it was designed to simulate.

The authors found that listeners cannot discriminate real from virtual sounds presented in this way. Moreover, the virtual sound remained perceptually identical to the real sound — even after most of the fine detail of the HRTF (both phase and magnitude) was removed. This does not mean that an individual HRTF is unimportant. But, for an accurate reproduction of real three-dimensional auditory space, it seems that a virtual space signal must compensate for only the most prominent features of the individual listener's HRTF.

Earlier this year it was shown[8] that if the pinna is modified using ear moulds, the ability to localize sounds (particularly in elevation) is dramatically reduced. But people can re-learn localization if they are given time to adjust to these new ears. Moreover, they can still localize sounds accurately using their own ears, immediately after the moulds have been removed. Perhaps there is a use for virtual environments that distort, rather than faithfully replicate, real auditory space. For example, by exaggerating the magnitude of the cues, it might be possible to train an

Electronic databases

It's good to talk

These days, electronic databases are the quickest, easiest way to search the scientific literature. But how good are they at finding all of the relevant studies? According to a study by F. D. R. Hobbs and colleagues (*Br. Med. J.* 317, 1562–1563; 1998), in developing fields at least, it may be better to rely on word of mouth.

The best way to find all studies relevant to a particular field is to hand-search the literature. In most fields this is difficult enough, but imagine the task in new fields, where the specialist literature has not become established and papers are widely scattered.

This is the challenge that Hobbs and colleagues took on. Having chosen a relatively new field known as 'near patient testing', they sent questionnaires to academics and commercial companies, requesting key references from journals and the names of other workers in the field. They then compared the answers with the results of searching eight databases.

KOBAL COLLECTION

Their results confirmed previous studies which showed that electronic databases may uncover only half of all relevant studies. Indeed, almost a quarter of the 'eligible' references would not have been discovered without the help of experts in the field. It seems that, in developing fields, there's still no substitute for seeking expert advice.

Alison Mitchell

observer to use a broader range of spatial channels.

The recent progress made in this field is not limited to human studies — some groups are using virtual auditory space methods to study the brain mechanisms for sound localization in anaesthetized animals[9]. By exploring neural responses to virtual-space signals, complex properties of receptive fields are revealed without the limitations inherent in using an array of speakers or a mobile sound source. However, because we have no behavioural measure of the animal's perception of the virtual sound, and because we cannot present both the virtual signal and its real counterpart, we do not know how well the virtual stimulus replicates real auditory space. These concerns could be alleviated by adapting the approach of Kulkarni and Colburn to physiological studies in behaving animals. ☐

Malcolm N. Semple is at the Center for Neural Science, New York University, 6 Washington Place, New York, New York 10003, USA.
e-mail: mal@cns.nyu.edu

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Nuclear fusion

Advanced fuels under debate

G. L. Kulcinski and J. F. Santarius

The energy released by the fusion of deuterium and tritium has long been touted as a replacement for power plants that burn fossil fuels (which, of course, emit huge amounts of greenhouse gases), and for fission reactors which generate long-lived, high-level radioactive waste. Not only is fusion technology struggling to overcome the difficulty in confining a deuterium (D) and tritium (T) plasma, and to attain commercial viability, it is struggling with the consequences of intense neutron bombardment of confining structures. Fuels that release far fewer neutrons would offer considerable advantages over the D–T cycle — hence a meeting* on the topic last month.

Deuterium and tritium are the principal first-generation fusion fuels, because they burn most easily. Alternative fuel cycles are being given serious thought because of the radiation damage and radioactive waste products that result from the D–T cycle, which emits 80% of its energy in high-energy neutrons. These neutrons are known to cause severe degradation of the structural components and generate large quantities of radioisotopes; D–T fusion produces four times as many neutrons as fission reactors per kilowatt hour of thermal energy released.

Advanced fusion fuels are defined as those whose neutron production rates are very low, or even zero. The second-generation fusion fuel cycles (for example deuterium–helium-3; see Fig. 1) release only a few percent of their energy in neutrons, whereas the third-generation fuels (proton–boron-11, helium-3–helium-3 and others) are essentially neutron free. In magnetic fusion technology, confinement of the fuel in the form of a plasma (ionized gas) is a central issue. The increased profile of advanced fuels coincides with the re-emergence of innovative confinement concepts, which are particularly suited to burn such fuels.

One of the main advantages of the second- and third-generation fuels is that they greatly reduce the radiation damage to fusion chamber structures, allowing these components to last the full lifetime of the power plant. These fuel cycles produce little or no long-lived radioactivity, thus reducing the expense of decommissioning a plant when its working life is over. They also release a large fraction of their energy in the form of charged particles, so they would allow direct conversion of fusion-product energy to electricity at efficiencies of 70% or higher. This is roughly twice what the first-generation fuels will attain with thermal conversion — the use of neutron-heated coolants to create superheated steam to drive turbines.

The main disadvantage of the second-generation fuels is that they require 4–5 times higher temperatures and 4–5 times better confinement conditions to compete with the first-generation fuels. The third-generation fuels require factors of more than 20. Generally, the second- and third-generation fuel cycles have lower fusion power densities. That is the reason why advanced fuels have to be coupled with new confinement techniques, such as those discussed at the meeting. Such techniques could have an intrinsically higher power density than the tokamak, currently the mainline approach pursued around the world.

One issue raised was that engineers might not be able to take full advantage of D–T fuel in the new, high-power-density approaches because of high neutron wall loads. The ^{3}He fuel cycles also have the problem of the location of a long-lasting fuel source. Although there is enough ^{3}He in the United States and Russia to conduct all the research needed to develop the first commercial fusion power plant, that amounts only to some hundreds of kilograms. Subsequently, much greater quantities (tens of tonnes per year) would be required for a worldwide fusion reactor economy, but the main relevant source (at around 1,000,000 tonnes) is on the Moon.

Four concepts especially suited to burning the second- and, in some cases, the third-generation fuels were aired at the meeting. A crucial distinction here is between Maxwellian and non-Maxwellian plasmas. Collisions force plasmas nearly to thermodynamic equilibrium, except for usually small flows through the physical boundaries, and the resulting plasma is said to have a Maxwellian distribution. Some concepts rely on input power or pulsed operation to keep the system far from equilibrium, and these plasmas are called non-Maxwellian.

The first of the approaches discussed has been proposed in a near-term, high-field, D–^{3}He experiment called CANDOR, based on Maxwellian plasma in a tokamak (B. Coppi and L. E. Sugiyama, Massachusetts

First generation	D + T	$\longrightarrow$	n + ^{4}He	17.6 MeV
	D + D	$\longrightarrow$	n + ^{3}He	3.65 MeV
		$\longrightarrow$	p + T	(av.)
Second generation	D + ^{3}He	$\longrightarrow$	p + ^{4}He	18.4 MeV
Third generation	p + ^{11}B	$\longrightarrow$	3 ^{4}He	8.7 MeV
	^{3}He + ^{3}He	$\longrightarrow$	2p + ^{4}He	12.9 MeV

Figure 1 **The main fusion reactions, and their energy yield. For instance, fusion of deuterium (D) and tritium (T) yields a neutron and helium-4, with release of 17.6 mega electronvolts of energy. The second- and third-generation fuel cycles result in very small or no release of neutrons (neutrons damage plasma-confinement structures — hence the reason, among others, for investigating the alternative fuels).**

**Advanced Fuels for Fusion*, miniconference at the Annual Meeting of the American Physical Society's Division of Plasma Physics (http://www.aps.org/meet/DPP98/), New Orleans, 19 November 1998.