configuration, with closed seaways around Antarctica and an unimpeded circulation around the Equator, must have produced a different ocean-circulation pattern.

Thomas[1] used an innovative geochemical approach to trace past deep-water circulation in the equatorial Pacific. Her method is based on the analysis of neodymium isotopes in the teeth and bones of fossil fish. The traditional way of reconstructing water-mass movements involves analysing the carbon-isotope signals in the calcareous remains of plankton in seafloor sediments. The advantage of neodymium-isotope tracers is that they are particularly robust against post-depositional alteration[9]. The basic concept is that deep-water masses of different origin can be identified by the neodymium signal inherited from the solutions and particulates that enter the ocean following weathering on land; this signal becomes incorporated into the hard tissue of the local fish. The potential sites of deep-water formation in the Atlantic Ocean, the Antarctic Ocean and the North Pacific were bordered by landmasses with different crustal ages, and therefore with different neodymium-isotope ratios, allowing them to be distinguished from one another.

The highlight of Thomas's study is her compelling evidence that, in response to the warm climate during the early Cenozoic, formation of deep-water masses switched from the southern high latitudes to the North Pacific. Thomas concludes that this switch was not a consequence of the prevailing ocean temperatures during that time, but that it was possibly triggered by a change in the spatial pattern of freshwater precipitation and run-off from land. This change apparently resulted in a freshening of the surface waters in the Antarctic, making them less dense, while those of the North Pacific became slightly saltier and dense enough to sink. When freshwater run-off from the continents is factored in, the existence of a 'downwelling cell' in the North Pacific is also predicted by model simulations of ocean circulation in the early Cenozoic[10].

Thomas's findings clearly underscore the notion that ocean circulation is altered during times of global warmth. But her identification of high-latitude downwelling in the North Pacific argues against the often-proposed mechanism that, during the early Cenozoic greenhouse interval, heat was transported towards the poles by the spread of tropical waters. This result helps to verify the conclusions deduced from model simulations[11], which also do not support that hypothesis. An overall lesson, then, is that a combination of both approaches — evaluation of geological records and computer-based modelling — is essential for understanding ancient climate systems. ■

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Neurobiology

Sleep on it

Ilana S. Hairston and Robert T. Knight

Is the function of sleep to replenish energy resources or to modify neural connections in the brain? Recordings of the brain's 'reverberating circuits' evident during sleep shed light on the question.

"With regard to sleep and waking, we must consider what they are: whether they are peculiar to soul or to body, or common to both; and if common, to what part of soul or body they appertain." This question was posed by Aristotle[1] in 350 BC. Although the dualist view of body and soul is not part of modern neuroscience, we are still at a loss to understand the function of sleep. On page 78 of this issue[2], Huber *et al.* provide elegant results that favour the role of sleep in neural plasticity and memory consolidation.

Sleep is homeostatically regulated — that is, prolonged wakefulness results in a proportional increase in the tendency to fall asleep[3]. The hallmark of the need for sleep is an increase in the brain's slow-wave activity, as seen in electroencephalographic (EEG) recordings during non-rapid eye movement (NREM) sleep, which is proportional to the time spent awake. This has led to the formulation of the two-process model of sleep regulation: one process that reflects the dynamics of homeostatic events, expressed as modulation of slow-wave activity as a

NATURE

100 YEARS AGO

Religion and Science: Some Suggestions for the Study of the Relations Between Them. **By P. N. Waggett, M.A. Pp. xii+174. (London: Longmans, Green and Co., 1904.)**

It is pleasant to find a book which seeks to deal from the religious standpoint with the relations between religion and science… The author speaks, with possibly undue modesty, of his own opinions on the "domestic" issues that divide biologists. Holding, as he does, that "natural selection remains scientifically the most probable and philosophically the most welcome account of the adaptations of animal and vegetable life," he is perhaps inclined to attach too much weight to the arguments that have been brought forward by various scientific authorities on the other side.

Buy English Acres. **By C. F. Dowsett. Pp. 224. (Published by the Author, Winklebury, Basingstoke.)**

This is not a book in the ordinary sense. It is a collection of miscellaneous arguments, extracts from books, and biographical notes, all intended to prove that pleasure and profit may be derived from the purchase of English land. The absence of any attempt at coherence or sustained economic discussion is atoned for, so far as possible, by the author's great earnestness. Apart from that, the book has no serious qualities.

From *Nature* 30 June 1904.

50 YEARS AGO

The Collected Papers of Peter J. W. Debye **Pp. xxii+700. (New York: Interscience Publishers, Inc.; London: Interscience Publishers, Ltd., 1954.)**

To celebrate the seventieth birthday of Prof. Peter Debye, this volume containing a selection of his classical papers has appeared. No one during the past forty years has made so many significant contributions to modern physical chemistry as has Prof. Debye: his name will always be associated with such topics as X-ray scattering, the theory of strong electrolytes, dipole moments and, during more recent years, with the scattering of light by colloidal solutions… While the book is an important one for purposes of reference, it is most valuable in that it gives us a glimpse of the methods of attack adopted by one who, trained as a mathematician, became in turn professor of theoretical then experimental physics and finally professor of chemistry, in which subject he received the Nobel Prize.

From *Nature* 3 July 1954.

M. ZAGARIS/C. CLAYWORTH

Figure 1 **Why sleep? Huber *et al.*[2] find that during slow-wave sleep (tracing at bottom) people improve their ability to perform a task that they had learned before going to sleep. The results provide evidence that slow-wave activity has a key role in learning.**

function of sleep–wake history; and another that reflects the circadian regulation of the sleep–wake cycle[4]. Sleep deprivation has serious and diverse biological consequences — from impaired cognitive function to perturbation of the immune, hormonal and autonomic nervous systems, and up to and including death.

Two prominent hypotheses have been proposed to explain the physiological function of sleep. One suggests that NREM sleep provides a period of low metabolic demand, during which a deficit in neural energy resources is replenished or intracellular 'housekeeping chores' are accomplished. Specifically, the metabolic demand during wakefulness is postulated to decrease the ATP:AMP ratio, resulting in high levels of extracellular adenosine, which in turn binds to adenosine (A1) receptors, inhibiting neuronal activity and lowering metabolic demand[5]. Put simply, high metabolic demand during wakefulness incurs an energy deficit, which is corrected during sleep.

A second hypothesis suggests that sleep has a key role in neural plasticity — that is, in maintaining appropriate connections between neurons through respectively reinforcing and eliminating significant and accidental connections between synapses. Owing to its traditional association with dreaming, REM sleep was first implicated in learning and neural plasticity, with findings — mainly from animal studies — showing a correlation between the amount of REM sleep and performance on a learned task[6]. More recently, NREM sleep, and specifically slow-wave activity, has also been shown to play a critical part in both developmental and learning-induced plasticity[7].

Both hypotheses predict that local neural activation due to specific cognitive demands will cause an increase in slow-wave activity during subsequent NREM sleep. It is important to note, however, that only the plasticity hypothesis predicts that such increased slow-wave activity would enhance performance during subsequent testing.

Huber *et al.*[2] provide results that favour the plasticity hypothesis. In their experiments, human subjects performed a complex task requiring hand–eye coordination before they went to sleep. This task typically involves the regions in the right parietal cortex of the brain[8]. Using a combination of techniques — an EEG system recording from 256 electrodes on a subject's scalp and magnetic resonance imaging — Huber *et al.* found that, during 'post-training' sleep, slow-wave activity was increased only in the regions of the right parietal cortex thought to be involved in this task. The authors also demonstrated that sleep enhanced performance in a subsequent re-test on the task.

These findings complement previous observations, in both rats[9] and humans[10], that showed that stimulating events induce local changes in slow-wave activity, and that the amount of NREM sleep predicts performance improvement[11]. But Huber and colleagues critically extend previous work by showing that the extent of the local increase in parietal slow-wave activity predicted performance enhancement in subsequent testing, thus supporting the view that slow-wave activity has a specific role in plasticity and learning.

The slow waves seen in EEG recordings are the result of synchronized oscillatory activity in cortical neurons. Work with *in vitro* preparations of neurons and with neural-network models has suggested that these slow oscillations are conducive to synaptic strengthening, thereby contributing to memory consolidation[12,13]. Support for this view has been proposed from rodent studies in which firing patterns of 'place cells' in the hippocampus, recorded in the awake animals, were found to be reactivated ('replayed') during subsequent NREM sleep[14]. Huber and colleagues' finding, that local generation of slow-wave activity is associated with enhanced performance, provides proof of concept for these models in humans (Fig. 1).

The new work[2] offers evidence that neural plasticity occurs during sleep. But does this mean that plasticity is the function of sleep? If only part of the brain is undergoing synaptic strengthening, why is it necessary for all the rest of the brain and body to sleep? Synchronous neural activity for plasticity needs could be generated locally in the brain, without the broad behavioural and physiological changes that occur during sleep and that potentially expose the organism to life-threatening danger.

It has been proposed that the entire cortex of the brain experiences neural plasticity related to updating experiences of the world, and dependent on the previous day's events[15]. If this were true, with appropriate testing one should be able to show that there are multiple regions of experience-dependent changes in slow-wave activity. But it remains to be seen how such regional changes would translate into the global dynamics determined by sleep–wake history. Conversely, it is possible that synaptic strengthening is an added benefit of slow-wave activity, which is actually driven by the need for metabolic recovery. Are these 'reverberating circuits' essential elements in the function of sleep, or are they a by-product of design for another purpose — are they, in fact, the spandrels of St Mark's of sleep research. ■

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