corrections to Newton's law to be consistent with experimental results.

This remarkable insight has stimulated a flurry of subsequent papers developing the ideas and determining the implications for cosmology and particle physics. Directions being pursued include verifying in more detail how four-dimensional general relativity emerges on the three-brane, and studying ways in which the framework can be embedded in string theory.

The implications for particle physics are particularly exciting because other closely related ideas published by Randall and Sundrum[2] may provide a resolution to the 'hierarchy problem', one of the most important issues in going beyond the Standard Model of particle physics. The Standard Model is a fantastically successful theory of three of the forces of nature: electromagnetism, the weak nuclear force and the strong nuclear force. It unifies electromagnetism and the weak nuclear force into the electroweak force at characteristic length scales of around 10^{-17} cm (roughly the limit of the scales probed by current acceler-ators). There are strong arguments that unifying particle physics with the fourth known force, gravity, into a theory of quantum gravity (string theory, say) will have a characteristic length scale of around 10^{-33} cm. It is very difficult to account for such a vast gap between these two scales without fine tuning the theoretical parameters to an extraordinary extent. This is the hierarchy problem.

The conventional approach for dealing with this problem is to invoke a new symmetry between matter and forces called supersymmetry, which could be detected by the next generation of particle accelerators. An alternative approach (which might also include supersymmetry) is to assume that our world is a three-brane. The first proposals[3,4] along these lines considered a single three-brane embedded in a space–time with at least two extra dimensions that are compact and flat. These dimensions could be as large as 1 mm without violating known experiments. In a string theory setting it is possible that the string length scale could be just below that probed by current accelerators, rather than about 10^{15} times smaller as previously supposed. These schemes are fascinating although they do introduce another hierarchy that needs explaining.

By contrast, Randall and Sundrum suggest that a curved ambient space–time with one extra dimension might provide a better setting. They consider a slab of this space–time bounded at each end by a three-brane. (Slabs of space–time bounded by branes were first introduced in string theory in ref. 5.) One of these branes is our world and the other is a 'hidden' world. Particles on our three-brane interact with the extra dimension and the hidden world through gravitational interactions. By assuming that the distance between the branes is very small, Randall and Sundrum showed that these interactions are weak enough to be consistent with experiment. They also showed how the hierarchy of scales on our three-brane can be accounted for in a fascinating way by the curvature of space–time without introducing any extra hierarchy.

The Randall–Sundrum papers do not provide a detailed model of particle physics beyond the Standard Model. Indeed there are considerable difficulties to be overcome to achieve this goal. But they have provided exciting alternatives to conventional ways in which people thought the unification of particle physics and gravity might occur. Particle physicists, string theorists and cosmologists are currently devoting much effort to developing ideas and deriving predictions that could be tested by the next generation of particle accelerators and gravity experiments. If Randall and Sundrum are on the right track, there could be exciting experimental evidence in the near future. ■

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Cognitive neuroscience

Imaging in the fourth dimension

Thomas Elbert and Andreas Keil

The 1990s, the decade of the brain, saw enormous developments in neuroimaging. Structural details of the brain can now be reconstructed non-invasively as three-dimensional images; and small, task-related changes in cerebral blood flow, even in the deepest recesses of the brain, can be seen. The principles of the functional organization of the brain are being uncovered, and it seems that not only initial processing stages but also complex aspects of perception and cognition can be mapped onto brain structures[1,2]. Nevertheless, cognitive neuroscientists find themselves in an odd, but perhaps not surprising, situation. As the number of studies increases, so does the number of conflicting results. On page 80 of this issue, Patel and Balaban[3] provide an example of what has been missing in neuroimaging — a new approach that adds time as the fourth dimension.

Usually, three-dimensional images of cerebral blood flow, metabolic changes or the activity of populations of neurons are

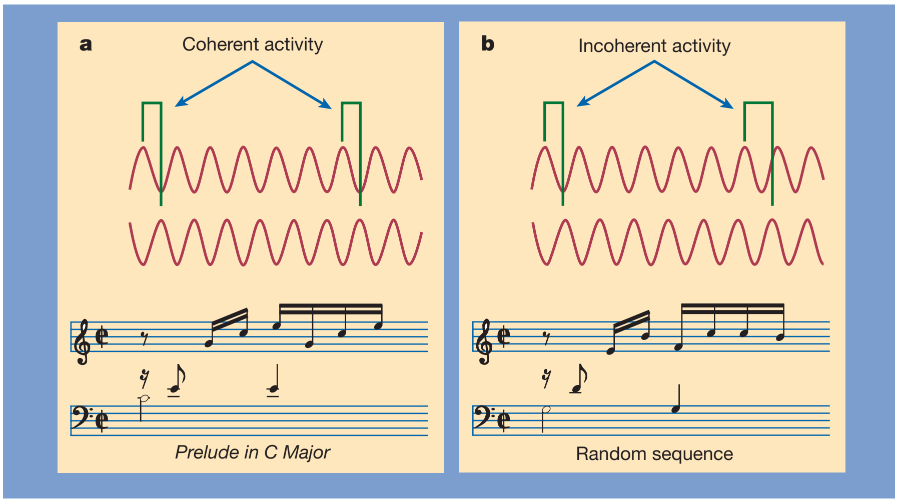

Figure 1 **Music and random notes produce different neural responses. Oscillatory brain activity evoked by repetitive auditory stimulation shows different temporal relationships between widely separated recording sites, depending on stimulus properties.** a, **Patel and Balaban[3] found that predictable, melody-like tone sequences are associated with coherent activity and more constant phase lags of oscillatory responses recorded from distant channels. This synchronization of brain activity in distant areas (the traces shown above the music) may reflect perceptual integration. The example shown here, Bach's *Prelude in C Major*, should produce high coherence.** b, **In contrast, a random sequence of tones showing identical rhythmic structure but no melody should produce incoherent activity of distant channels, with less synchronization between brain regions.**

acquired during a given task or perceptual activity (while the subject is listening to Bach's *Prelude in C Major*, for example). The temporally static image can account only for a static cerebral response. But the brain's response is actually dynamic and self-organizing over time. So the perception of music and its neural code must be reflected in the neural dynamics — in both space and time. It is not only important to identify the neurons, neuronal assemblies or brain regions that respond to a given input. We must also develop techniques that allow the systematic classification of the temporal dynamics underlying elements of information processing. But adding time as the fourth dimension to three-dimensional space is not easy.

Patel and Balaban[3] study brain dynamics using stimulus-related magnetoencephalographic responses. Subjects hear different sequences of tones that are switched on and off in rapid, 40-Hz sequences. Examination of the stimulus-related brain response that cycles at 40 Hz, the so-called steady-state response, allowed Patel and Balaban to determine how the timing of neural responses varied with different tone sequences. They found a relationship between the phase (but not the signal power) of the steady-state response and the frequency of the acoustic stimulus. That is, the timing of the neuronal response depended on the properties of the stimulus.

Intriguingly, these phase fluctuations vary with the structures of the tone sequences. Between-site phase coherence, which indicates synchronized activity between brain areas, was most pronounced for tone sequences that resembled melodies. Generalizing this outcome, the *Prelude in C Major* should produce higher inter-channel phase coherence than the same tones shuffled in random sequence (Fig. 1). Would Bach do better than the Beatles? We do not know, but now we can study how limited brain regions track the changes in pitch of auditory sequences as a piece of music is played.

Steady-state responses are a valuable tool for monitoring activity in different sensory modalities. To exploit this approach fully, we will need to understand how such brain responses are produced. In general, if the interval between successive stimuli is short enough, the transient evoked response to one stimulus will not have died away before the next stimulus is delivered. The compound response that appears is the steady-state response. There are various ways in which transient responses can sum over time to produce a steady-state response, and these fall into two groups. For a linear system, transient and steady-state descriptions of the system's behaviour are equivalent, and a simple superposition of transient evoked responses with the appropriate time lags should fully predict the steady-state responses[4]. However, neural assemblies are nonlinear elements. If a nonlinear system is stimulated periodically, harmonics, combination frequencies and subharmonic components may evolve[5].

Neither of these simple principles of organization accounts for the observation by Balaban and Patel that the phase of the steady-state response follows the pitch of the auditory stimulus more strongly for scales than for melodies. Obviously, higher areas of brain influence the auditory cortex and related structures by 'top-down' processes, tuning their responses according to contextual cues and previous learning. So coupled oscillations between higher-order and sensory cortices may explain why what sounds like noise to an adult is music to the ears of a teenager.

Attempts to segregate brain function into distinct modules are limited because the nervous system tends to operate through the intercommunication of task-relevant subsystems. So the simplistic modular approach needs to be complemented by modelling, in space and time, the network that incorporates the different modules. In the visual system, several different types of discrimination can be processed in the same small area of cortex. A similar phenomenon has been seen in the motor system[6]. Likewise, a single type of stimulation of two digits can produce two opposite, use-dependent effects on the spatial relationship of the cortical representations of the digits, depending on the nature of the discrimination condition used[7]. In other words, multiple maps, specific to different modes of discrimination or tasks, share the same region of cortex. So the three-dimensional modular approach provides us with seemingly conflicting results: there are many three-dimensional shadows in a four-dimensional world. It is time to add time! ■

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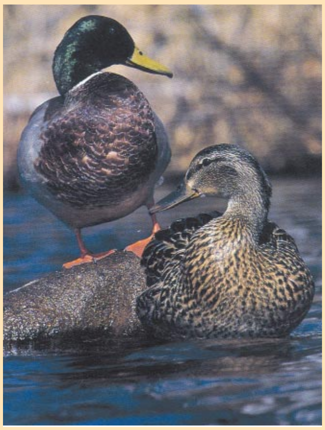
Animal biology

Beauty is ova-rated



SCOTT NIELSEN

Female ducks are choosy when it comes to mating. Some male mallards (*Anas platyrhynchos*) are much more attractive to females than others, and females that mate with these 'preferred' males seem to raise more chicks to adulthood. It has generally been assumed that this bias reflects a genetic advantage conferred by the father.

Elsewhere in this issue (*Nature* **404,** 74–77; 2000), Emma Cunningham and Andrew Russell propose a different explanation. They have compared the clutches of eggs produced by females after mating with more attractive males with those produced by females mated with less attractive males. They find that pairings with preferred males result in bigger eggs being laid.

Chicks that hatch from large eggs are more likely to survive the critical first few days after hatching. So the higher viability of the offspring of attractive males may have nothing to do with the genetic legacy of the father — instead, it may result from increased maternal investment in the eggs. When Cunningham and Russell controlled for egg size, the attractiveness of the father made no difference to the health of the chicks.

So why do female ducks invest more energy in eggs that are fathered by more attractive males? It is likely that male attractiveness is linked to some characteristic that makes their offspring more successful in the long run. Females would then invest more in these eggs to further their own breeding success.

Male mallards are not good fathers — females do all the work of rearing chicks. So males cannot be selected by females for their paternal qualities. But they do defend feeding areas around their mates during the breeding season, so attractiveness may be linked to the ability of a male to fend off other mallards. This ties in with the fact that females prefer males from early-hatching clutches, who tend to be bigger and stronger.

Cunningham and Russell point out that researchers need to be careful, when studying the influence of male attractiveness or dominance on the viability of offspring, to allow for the effects of differential maternal investment rather than attributing all differences to paternal genetics. **Rachel Smyly**