consume atmospheric oxygen. Atmospheric oxygen levels can therefore rise only when photosynthesis and carbon burial produce more oxygen than is sufficient to oxidize the volcanic gases[13]. This observation has led to a widespread suspicion that a change in the oxidation state of volcanic gases somehow controlled the timing of the rise in atmospheric oxygen. The change in volcanic-gas oxidation state could, in turn, reflect an alteration in the oxidation state of Earth's interior[14,15], or, alternatively, changes in factors such as the rate of volcanism or the depth at which magmas stagnate and de-gas[7,16,17].

Keller and Schoene add another hypothesis to this list, by proposing that the generation of granitic magmas at shallower depths was responsible for the rise in atmospheric oxygen. The chemical signature of Archaean granitic magmas suggests that they were generated at sufficient depth to leave an eclogitic residue (a mixture of the minerals garnet and pyroxene), whereas that of post-Archaean intra-crustal magmas suggests that these were generated at shallower depths and left a gabbroic residue (a mixture of olivine, pyroxene and plagioclase). Ferric iron — the oxidized form of iron — seems to be more compatible with eclogitic residues than with gabbroic ones, and so the authors speculate that an accumulation of ferric iron in eclogitic minerals may have caused the Archaean magmas, and their associated gases, to be more chemically reduced than post-Archaean ones.

The Archaean–Proterozoic boundary seems to have been when Earth came of age: a time when the planet passed from energetic, exuberant youth to more sedate middle age. But because the transition occurred an extremely long time ago, the corresponding geological record is sparse. Cause and effect have yet to be fully deduced for events that occurred around that time, but the record seems to show that processes in Earth's interior and at its surface, including the evolution of both climate and life, are intimately linked. Those events set the stage for the much later emergence of multicellular life including, ultimately, us. ■

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NEUROSCIENCE

Crystal-clear brains

An ingenious technique allows the monitoring of brain-wide patterns of neuronal activity in a vertebrate at the cellular level, while the animal interacts with a virtual environment. SEE ARTICLE P.471

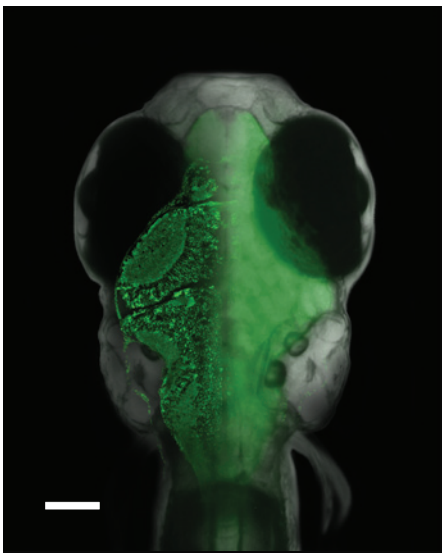
JOSEPH R. FETCHO

Neurobiologists studying brains face an enormous problem. They must deal with massive numbers of neurons — perhaps as many as 100 billion in a human brain — that interact with one another to produce the electrical activity that drives behaviour. Moreover, both the interactions and the activity change constantly as animals learn to modify their behaviour as a result of experience. How can the problem of interpreting such dynamics be addressed? One initial step is to monitor the activity of every individual neuron in the brain to reveal activity patterns during a particular behaviour, and to observe how those patterns change with experience. This is exactly what Ahrens *et al.*[1] have done for the first time using a vertebrate animal model. On page 471 of this issue, the authors describe how they imaged the activity of individual neurons throughout the brain of zebrafish larvae while the animals interacted with a changing virtual environment and adjusted their behaviour accordingly.

Most animals are opaque, so obtaining images of their brain with the resolution needed to see individual neurons (tens of micrometres or less) might seem impossible. But Ahrens and colleagues used a small, transparent vertebrate that is amenable to genetic manipulation — the larval zebrafish (Fig. 1). To detect the nerve cells that were active at any given moment, the authors introduced into the animal a gene coding for a fluorescent calcium indicator, which labels brain neurons and becomes brighter as calcium enters electrically active cells[2–4]. This, combined with advanced optical methods (such as two-photon microscopy), allowed the researchers to see the active neurons light up anywhere in the brain.

The authors set out to study a key problem in neuroscience: how do patterns of neuronal activity change throughout the brain as an animal modifies its behaviour when it learns something new? Fish adjust how strongly they activate their muscles by using visual feedback about how quickly the world is passing by as an indication of the speed at which they are moving. To facilitate imaging while fish learned to make these adjustments, Ahrens *et al.* immobilized zebrafish larvae by injecting them with a paralysing agent, and put them into a simulated virtual environment. Using computer monitors, the researchers controlled the rate at which the virtual world seemed to move past when the fish tried to move. The virtual scenes changed according to the animals' intended movements, which were inferred by the detection of electrical signals from nerves connected to the muscles that would normally produce the movements.

By changing how fast the world seemed



M. AHRENS, HARVARD UNIV.

Figure 1 | Illuminating behaviour. Ahrens *et al.*[1] monitored neuronal function throughout the brain of zebrafish larvae while the animals performed a learning task. Overlaid on an image of the fish is an image of a slice of its brain, as obtained with a laser scanning microscope, in which neurons are labelled with a green fluorescent calcium-indicator protein. Scale bar, 100 micrometres.

to move past when the paralysed animals attempted to activate their muscles, the authors tricked the fish into thinking that their muscles were suddenly weaker or stronger than normal. The fish learned to compensate for the changes by altering the strength of muscle activation to allow them to control their movements in the changing virtual environment.

The authors found that, even in the relatively simple brain of the larval zebrafish, the neurons that showed increased or decreased activity during learning were widespread. As expected, some of these cells were located in regions that receive information from the eyes as well as in others involved in producing the movements. Other brain areas that changed activity included the cerebellum and the inferior olive, which are crucial for complex control of movements, and the pallium in the front of the brain, a higher-level processing region. Of note, these changes in activity patterns, although extensive, are probably an underestimate of the extent of the changes that occur during learning — although the researchers' approach is the most powerful available, it is prone to missing small changes in the activity of individual neurons.

Nonetheless, Ahrens and colleagues' work faces head-on the problem of the complex ties between the brain and behaviour. Although behaviour is known to emerge from the activity of, and the interactions among, neurons across many brain regions, neurobiologists typically focus their research on just one of these regions at a time because of the technical difficulties associated with brain-wide studies at the cellular level. Mapping activity patterns at the single-cell level throughout a brain while the animal is learning is a major step towards a more integrated view of how neuronal circuits, in their entirety, drive behaviour.

The authors' study is a remarkable achievement, but documenting the patterns of activity everywhere in the brain is just the beginning of the task ahead. Many important details about the neurons whose activity changed during Ahrens and colleagues' experiments are unknown. We need not only a broad picture of the activity at the cellular level as provided by the authors' work, but also information about whether the neurons excite or inhibit other cells and how they connect to other neurons in the brain to form the circuits that drive behaviour. This is the focus of 'connectomics', an effort to map all of the connections in the brain[5]. Once neuronal activity, and both structural and functional connectivity, are mapped, models of the way in which circuits throughout the brain produce and modify behaviour must be formulated and tested. A powerful technique for this purpose is optogenetics[6], which allows neurons to be turned on and off with light during behaviour to test the contributions of different sets of cells — an approach that is especially applicable to a transparent animal. Therefore, all of the necessary tools for mapping activity and connectivity, and for testing neuronal function on a large scale, are now at hand and promise to provide increasingly complete pictures of behaviour-generating circuits throughout the brain.

The larval zebrafish will probably remain at the forefront of these efforts because of the powerful combination of optical, genetic and behavioural approaches that can be used to study it[7]. These larval fish show most of the behaviours typical of adult vertebrates, although some aspects of their behaviour are not as highly refined as that of adult fish or mammals. Most importantly, in no other vertebrate animal model is it possible to accomplish cellular-level-resolution imaging of the entire brain. The tools to map connectivity and perturb neuronal activity are also easily applied to this small, transparent fish, making it the best hope among vertebrate models for revealing how neurons throughout the brain interact to produce behaviour[8–10]. With the help of a tiny fish, a long-standing, but distant, goal of neuroscience is finally moving into view. ■

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PARTICLE PHYSICS

A reminder of the beauty we know

The latest measurements of the mass of the W boson, one of two elementary particles that mediate the weak nuclear force, are a powerful reminder of the profound beauty in the standard model of particle physics.

JONATHAN BUTTERWORTH

The most precise measurement so far of the mass of the W boson is reported by researchers in the CDF Collaboration (Aaltonen *et al.*[1]) at the Tevatron collider, Fermilab, near Chicago, in *Physical Review Letters*. The W boson is the particle that carries the weak nuclear force, which is responsible for radioactive β-decay. The particle decays in less than one billion-trillionth of a second, and many of the things that it decays to are hard to detect. The measurement of its mass is an experimental tour de force, a consistency test for the standard model of particle physics, and a pointer that will aid the discovery of new phenomena at the Large Hadron Collider (LHC) at CERN, Europe's particle-physics laboratory near Geneva, Switzerland.

The 'standard model' is the rather prosaic name given to the collection of quantum field theories that describes the Universe at the shortest distances and highest energies. You will often hear particle physicists hoping for physics 'beyond the standard model' because an anomalous experimental result might help to resolve some of the issues left unexplained by the model. These problems — including why the Universe contains more matter than antimatter, and where gravity fits in — are discussed so often that it is easy to forget how accurate and economical the standard model is.

In the model, the fundamental forces are carried by particles known as gauge bosons. The photon, for example, is the gauge boson that carries the electromagnetic force, whereas the W and Z bosons mediate the weak force. Bosons are particles that have an integer quantum of intrinsic angular momentum, otherwise known as spin. 'Gauge' means that the particles are generated by mathematical symmetries.

Symmetry is a central feature in the standard model. For the model to work in its most symmetric form, the W and Z bosons should, like the photon, have zero mass. This is not the case. Yet without symmetry, the standard model loses all predictive power — a finding[2] that earned Gerardus 't Hooft and Martinus Veltman the Nobel Prize in Physics in 1999.

The way out of this impasse could be supplied by the discovery of the Higgs boson. Its existence would indicate that symmetry remains in the standard model at high