magnetic field does not decay (it is unclear whether it does or not), the pulsar’s evolutionary track will remain horizontal, otherwise its path will become curved in the direction of a decreasing field. As the pulsar period becomes longer, the mighty particle accelerator gradually loses its power. Ultimately, after some $10^{10}$ years, when the maximum available potential drop becomes less than the critical value, radio emission from the pulsar will turn off — it will enter ‘death valley’ and disappear from the radio sky. Evidently, pulsar J2144–3933 does not quite fit in the above picture. Although its rotation period is almost twice as long as the 5.1-second period of the previous record holder, the pulsar has managed to stay alive in the region of Fig. 1 reserved for the dead. Pulsar J2144–3933 also does not belong to the group of ‘recycled pulsars.’ These are the most rapidly rotating neutron stars — so-called millisecond pulsars — which succeed in coming back from the ‘graveyard’ in Fig. 1 by acquiring mass and angular momentum from a binary companion. Pulsar J2144–3933, apart from its unusually long period, looks normal enough as far as its other properties are concerned. This includes the very narrow pulse profile and its polarization characteristics, both of which are in agreement with empirical models.

The discoverers’ of this peculiar pulsar list several interesting ideas that may help unravel the mystery of its existence. The rotation period of the pulsar is similar to the periods of unusual X-ray pulsars equipped with superstrong ($\sim 10^{15}$ Gauss) magnetic fields. In principle, pulsar J2144–3933 could be related to these ‘magnetars’ despite the fact that the pulsar’s own magnetic field is much weaker ($2 \times 10^{12}$ Gauss). Another possibility is that the geometry of the magnetic field lines in the emission region sufficiently departs from that of a simple dipole, meaning that the death valley can be moved towards longer rotation periods. Finally, one can question our understanding of the basic properties of neutron stars, or postulate an alternative radio-emission mechanism. It is clear, however, that a really meaningful discussion of these and other alternatives will depend on new detections of very slow pulsars like J2144–3933.

The authors are probably right in predicting that pulsar J2144–3933 must be the tip of the iceberg of a sizeable population of slowly rotating pulsars that may be difficult to pin down. The newly discovered pulsar is intrinsically weak and has a very narrow emission beam, as expected of very old, slowly rotating neutron stars. For these reasons alone, it may be difficult to detect more such objects in the near future. Moreover, in the recent past, pulsar searches have been driven by a desire to find ever more millisecond pulsars that may offer glimpses of new and exotic phenomena. In fact, the work by Young et al. dramatically demonstrates how easy it is to overlook a boring ‘vanilla flavour’ object during a highly automated pulsar survey. As a result, the existing vast databases will have to be sifted through once again, this time with the sights set at the long-period end of the pulsar rotation spectrum. Similarly, new and continuing survey data will most certainly be analysed with the aid of algorithms that are sensitive to super-slow pulsars. The detection of just one more object of this kind will certainly add a new, decidedly non-vanilla flavour, to studies of the pulsar emission mechanism.

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**Cognitive neuroscience**

How do you pay attention?

**Jeremy M. Wolfe**

It has been dry in eastern Massachusetts and, as a consequence, we have been watering the tomatoes. There are two ways to water tomatoes. One is to take the hose or watering-can and go from plant to plant, watering each in ‘series’. The other is to spray the entire patch, watering all the plants at the same time in ‘parallel’. If visitors arrive after the job is done the tomato patch will obviously be wet, but it will not be clear whether the deployment of water was serial or parallel.

Although this serial/parallel distinction may be of minimal importance in the watering of suburban vegetables, it has been central in attempts to understand our ability to process visual information. Your eyes present your brain with more information than it can fully process. So, for example, even if the print was made large enough, you could not read this article at the same time as you read another. You must select, or ‘attend’, one chunk of text. To understand how we see, we must understand how we attend. The results of the latest attempts to distinguish between serial and parallel modes of attention are reported by Woodman and Luck on page 867 of this issue. These findings favour the serial view.

To appreciate the serial/parallel distinction in attention, look for the ‘C’ that opens to the left in Fig. 1. Although the letters are large and easy to see, you probably spent some time searching. You might have been deploying your attention from ‘C’ to ‘C’ in a serial manner. Alternatively, you may have been processing all the Cs in parallel — then your ability to identify the orientation of the C would have been slowed by the need to spread your resources over several Cs at once.

We can make various indirect measurements of this search process. For instance, on average, it takes longer to find a left-facing C among 20 other Cs than to find the same target among just ten Cs. Typically, it will cost about 50 ms to process each additional item. Similarly, it would take longer to water 20 plants than ten plants, but this is true whether the watering technique is serial or parallel. (That is, unless the hose has infinite capacity. In that case, all plants could be watered in an instant. No real hose has unlimited capacity, but some models of attention feature such processes.) Although there are some very sophisticated approaches to teasing serial or parallel conclusions out of indirect measures such as response time and accuracy, a firm answer has remained elusive. What we really want is a chance to see the attentional ‘gardener’ in action.

There are several ways to look at attentional effects in the brain. Using functional magnetic resonance imaging, for example, we can see a ‘spotlight’ of attention illuminating some parts of the field of view and not others. But the temporal resolution of the...
method has been too coarse to distinguish serial from parallel deployment. Electrophysiological recordings from single neurons can also reveal the effects of attention\(^8,9\), but they have not yet been used to assess the spatial and temporal dynamics of attentional shifts.

To try and visualize the deployment of attention, Woodman and Luck\(^10\) used event-related potentials (ERPs) — scalp recordings of electrical activity in the human brain. ERP data are the changes in recorded voltage as a function of time since a certain event (hence the name ‘event related’), and these waveforms have several useful attributes. First, their temporal resolution is fast enough to see shifts of attention that might occur within 50–100 ms. Second, their spatial resolution is at least adequate to tell the difference between stimuli in the left and right halves of visual space. Finally, an ERP waveform with the catchy name of N2pc has been shown to be associated with attentional selection\(^11\). By examining changes in N2pc during visual-search tasks, Woodman and Luck believe they can prove that the mental tomato plants are being examined in series.

In one version of their experiment, subjects saw a field of rotated Cs. One of these Cs was red and another was green. Subjects were told that the target, if present, was three times more likely to be the red C than the green one. This should bias subjects either to attend first to the red C (if they are attending in series), or to allocate more attention to that item (if they are attending in parallel). Suppose that the likely (red) item is on the left side of the display and the unlikely (green) item is on the right, then consider what happens when the unlikely item is the actual target.

If attention is deployed in series, an N2pc response to the likely item should appear first in one cerebral hemisphere. It should be quickly followed by a response to the unlikely item in the other hemisphere. A model of parallel attention, on the other hand, might predict responses of different sizes to the different stimuli, but the time course of the response should be similar for both stimuli if they are both processed at the same time. In three versions of this experiment, Woodman and Luck found that the switch of the signal was consistent with serial deployment of attention. Moreover, the delay between the two N2pc signals agreed quite well with other estimates of the speed of serial attentional shifts.

Will one study resolve this long-standing controversy? Probably not. There are many parallel models of attention, and their supporters are very resourceful. For example, one could argue that attention is allocated to both items, but that more is given to the more likely item. The electrical signal of that attention would then become measurable at the likely location first. Although this one line of hand-waving is not a theory, others are sure to appear before long offering more compelling ‘parallel’ accounts of this ‘serial’ finding. Nevertheless, even if Woodman and Luck’s result turns out not to be definitive, it is a considerable advance because it places strong constraints on models of attentional allocation.

Why has it been so difficult to resolve the serial/parallel debate in the study of attention? Perhaps labelling attentional deployment as serial or parallel is like describing light as a particle or a wave — different experiments reveal particle- or wave-like properties of light. In the same manner, attention may appear serial or parallel to different experimental probes. As an analogy, think about a car wash\(^12\). Cars enter and leave the car wash in series. However, at any given time, several cars can be washed. Is this a serial or a parallel process? One can imagine ‘multi-lane’ car washes that would further blur the distinction\(^13\). Seen in this light, Woodman and Luck’s result illustrates one, apparently irreducibly serial, aspect of the complex attentional machinery that selects some parts of the visual world for more extensive processing.

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**Biological oceanography**

**Complex lessons of iron uptake**

**Richard J. Geider**

Oceanographers often speak of physical or chemical pressure on primary ocean productivity (that is, the photosynthetic conversion of CO\(_2\) to new organic matter), but there is increasing evidence that marine phytoplankton also influence the fertility of the sea through production and consumption of dissolved organic compounds. This is the case for copper, which is detoxified by the release of specific organic ligands into the sea by planktonic bacteria\(^1\). It is also true for iron dissolved in the sea, of which 99% is bound to organic ligands in a way that actually increases the availability of this essential nutrient\(^2\).

Dissolved iron is present in very low concentrations in sea water (10\(^{-10}\)–10\(^{-11}\) moles kg\(^{-1}\)) and in the absence of organic matter would be even less, because free iron would precipitate at the surface as oxyhydroxides or be adsorbed onto sinking particles. So, organic ligands help to retain iron near the sea surface where there is sufficient light to support photosynthesis. But ligand-bound iron is a problem for species of phytoplankton that cannot transport these organic complexes across their plasma membrane, raising the question of how these organisms obtain iron. On page 858 of this issue, Hutchins and co-workers\(^8\) present convincing evidence that different groups of phytoplankton are capable of accessing iron that is tightly bound to organic matter using different mechanisms.

Iron was thought to be a potential limiting factor in marine productivity after studies of plankton growth in the Southern Ocean early this century\(^3\). But it was only with the introduction of ultraclean sampling techniques in the 1980s that iron was shown to be a limiting nutrient, in at least 30% of the world’s oceans\(^4\). This was not always the case. Prior to the evolution of oxygen-producing photosynthesis about three billion years ago, iron was present at much higher concentrations in the ferrous (Fe(II)) oxidation state. With photosynthesis, the oxidizing conditions in the oceans led to ferric (Fe(III)) iron being precipitated, and a drop in the concentration of dissolved iron. In a perverse twist of fate this created an energy crisis for photosynthetic microbes, because large amounts of iron are used in both photosynthetic and respiratory electron-transfer chains\(^5\).

This energy crisis continues today in areas where iron is limited, particularly where light levels are low, such as the Southern Ocean\(^6\). Iron is also likely to be crucial to nitrogen-fixing organisms because the enzymes involved need large amounts of iron\(^7\). In the recent past, the drop in atmospheric transport of iron-laden dust from land to oceans during interglacial episodes may have been a contributing factor in glacial and interglacial variations in phytoplankton growth. Today, the oceans may be finely balanced between iron shortage and sufficiency, and increases in dust supply arising from global climate change could lead to sudden jumps in ocean productivity.

The nature of iron-binding ligands in sea water is poorly known, although there is evi-