suggest that orientation or direction preference may originate not in the cortex, but in a population of orientation- or direction-tuned neurons upstream in mouse LGN, as reported previously[13–15]. Lien and Scanziani[11], however, did not find significant orientation-tuned responses in the LGN, and they argue that the spatial offset of ON and OFF subregions is sufficient to give rise to orientation selectivity without involving tuned thalamic neurons (**Fig. 1c,d**). Their argument is supported by the observation that the net thalamic excitatory charge was largely untuned (that is, the integral of excitatory current was the same irrespective of stimulus angle), whereas the grating phase–modulated component of thalamic excitation was much more selective (**Fig. 1a,b,e,f**). Although this argument may explain the emergence of orientation selectivity in the absence of orientation-tuned thalamocortical input, it does not, however, reveal how layer 4 neurons acquire directional selectivity, which likely depends on mechanisms not described here. There are two possibilities that could explain why orientation- or direction-selective thalamic neurons may not directly contribute their preference to layer 4 neurons in mouse V1: either thalamic neurons converging onto the same cortical neuron are not tuned to the same orientation or orientation-selective thalamic neurons provide input to other cortical cell types or layers, which were not examined in these studies. Resolving this issue merits further work, as it is important to establish whether the mechanisms giving rise to cortical feature selectivity are similar across mammalian species.

In summary, one function of the intracortical excitatory circuit may be to increase the gain and duration of sensory signals in layer 4. Several important questions remain. The effect of excitation on the spiking output of a layer 4 neuron is strongly influenced by intracortical inhibition, which was not examined in these studies. It will be important to determine whether inhibition in layer 4 simply acts as an additional gain control mechanism or whether it influences the integration of excitatory inputs in a more specific way; for example, to generate directional preference in visual cortex. Moreover, what is the function of local and long-range intracortical excitation in other cortical layers in the transformation of sensory signals, as these may have additional roles in contextual processing or the spatial integration of signals across sensory scenes? As the arsenal of available techniques grows, we are inching closer to uncovering the precise rules that govern the nature of intracortical excitatory interactions and the sensory computations they subserve.

### COMPETING FINANCIAL INTERESTS

The authors declare no competing financial interests.

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# 10,000 hours to perfection

## Chris Miall

**A study reports that a metabolic measure of synaptic activity in the motor cortex becomes dissociated from neural firing rates after extensive practice in a behavioral task, suggesting an increase in efficacy of synaptic inputs.**

It is widely accepted that expertise takes practice—hence the ‘10,000-hour rule’ that intense practice for up to 10 years distinguishes expert performers from the merely good[1]. But what is the neural consequence of such extended practice in a particular domain? How are knowledge that is learned and skills that are gradually refined reflected in neural activity? For obvious reasons, there are few studies of the effects of very long-term practice on architecture or function in the human brain. Perhaps the most extensive are longitudinal studies that last weeks or months—well short of 10,000 h. For example, the acquisition of juggling skills over 6 or 12 weeks leads to changes in the volume of gray matter in visual motion areas and to changes in the white matter linking these motion areas to parietal sensory motor regions[2]. More typically, studies report the effects of a few tens of hours of practice spread over several days. In this issue of *Nature Neuroscience*, Picard, Matsuzaka and Strick[3] report the neural outcome in the monkey of training that lasted months and years.

In a study that is out of the ordinary for its duration, as well as for its conclusions, the authors trained ten monkeys to each perform two of four sequential reaching tasks. The monkeys were required to reach to targets displayed on a touch screen for water rewards. The four tasks included two visually guided tasks, in which the target sequences were either randomly presented or required tracking across sets of three, and two internally generated tasks, in which the targets repeatedly appeared in the same position or in a sequence that the monkey held in short-term memory. All of these monkeys were trained for more than 7 months: three of them for more than 30 months and a fourth for more than 6 years. The authors argue that, although there were no gross differences in the kinematics of the movements, the monkeys learned a skill in the internally generated tasks, whereas they were only able to reactively follow the unpredictable targets presented in the visual guided tasks. At the end of these extended periods of behavioral training, each monkey performed one of the two trained tasks after administration of [$^{14}$C]2-deoxyglucose (2DG) in a terminal experiment. Uptake of the tracer was then examined post-mortem.

The 2DG technique can be used to assess metabolic energy consumption and is thought to represent a measure of presynaptic activity. It is a measure closely related to the most common signal recorded in functional magnetic resonance imaging (fMRI), the blood oxygen level–dependent (BOLD) signal[4]. This gave Picard *et al.*[3] a measure of the synaptic activation of the primary motor cortex across the two task categories (internally generated versus visually guided). It is striking that, across the five monkeys performing the internally generated tasks, there was very low 2DG uptake in

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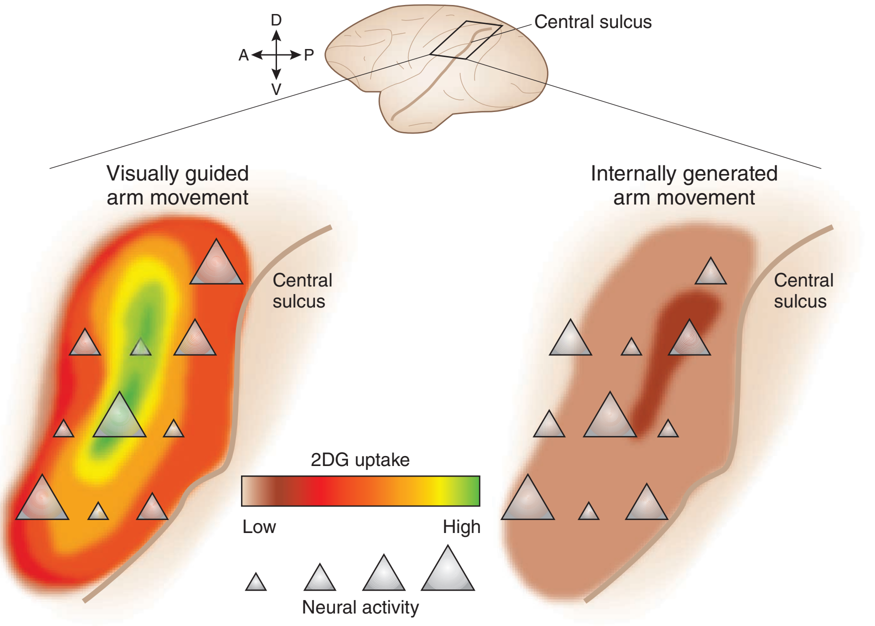
Chris Miall is in the School of Psychology, University of Birmingham, Birmingham, UK.
e-mail: r.c.miall@bham.ac.uk



Katie Vicari

**Figure 1** 2DG uptake maps of the motor cortex. The inset shows the location, around the primary motor cortex in the monkey. 2DG uptake (color coded) in the hand and arm areas of M1, anterior to the central sulcus was high for monkeys performing visually guided reaches (left) and low for those performing internally generated reaches (right). However, overall single-unit firing rates (indicated by the size of the markers mapping the recording locations) were comparable during the two tasks.

the arm area of primary motor cortex (M1) (**Fig. 1**). In fact, it was comparable to that seen in other monkeys that just performed licking actions (recall that the test monkeys were working for liquid rewards) without overt arm movements. In these control experiments, the authors found strong uptake in the mouth area of M1, but not in the arm area. However, in the other five monkeys performing the visually guided tasks during 2DG uptake, there was extensive activity across the arm and hand area (**Fig. 1**). Thus, it seems that, after months or years of practice, the monkeys are able to perform these internally driven actions without strong input to the cells in M1, whereas externally guided actions do evoke this activity.

But had the activity maybe moved elsewhere? There is good evidence that consolidation of motor memories into long-term skills involves reorganization[5] and spatial relocation[6] of memories. Picard *et al.*[3] addressed this by recording single-unit activity in the motor cortex of the same monkeys while they performed the two tasks. Activity was also recorded during the final 2DG experiment, although, by necessity, the monkeys were constrained to doing just one task each during the 2DG uptake session. What the team found was a dissociation between M1 neuronal firing rates, which were comparable between the two tasks when averaged across a population of several hundred neurons, and the 2DG uptake, which was elevated only in the visually guided tasks. Picard *et al.*[3] conclude that extensive training in the internally generated action tasks resulted in greater efficiency in the activation of M1: its neurons achieved equivalent firing rates with less presynaptic input.

This result is important and thought provoking. Its importance lies in its implications for understanding the rewiring of brain circuits to compactly encode information. The idea that the brain becomes more efficient is not new, and others have suggested that information becomes more sparsely coded; for example, in the storage of vocal sequences in songbirds[7]. But the dissociation between inputs (2DG) and outputs (firing rates) means that neither on its own can be considered a reliable measure of the contribution of a brain area to a task. We need to be able to measure both, ideally at the same time. This is not easy, and the provocative message from this work is that we cannot use BOLD signals alone to understand the brain's outputs: again, not a new message, but one worth heeding. BOLD, like 2DG, measures the synaptic input activity, and a small input seems to be able to drive a strong output after training.

Of course, M1 is not the final arbiter of muscle activity[8], and the separation of 2DG and firing in M1 between these two tasks may not hold for all areas. It is quite possible that other sensory-motor circuits become more active in the visually guided tasks and independently influence the spinal outputs. It is also possible that the 2DG and recording experiments were effectively sampling separate populations in the same cortical columns. Recording electrodes are better able to record action potentials from larger cells, and small cells or cells with low firing rates can be overlooked.

Interestingly, a recent study[9] found that the fine-scale distribution of activity within M1, recorded with BOLD, changes with learning. A multi-voxel pattern classifier can then more accurately classify finger sequences after several days of training. In other words, the pattern of BOLD activity across a small patch of cortex becomes more informative than its average signal. In fact, the average BOLD signal either did not change or decreased with training, consistent with a more efficient encoding of the learned skill.

It is increasingly obvious that we need to consider the effect of learning on the inputs and outputs of brain networks, measuring their changes across both short timescales with large spatial scales (for example, ref. 10) and across long timescales with fine spatial scales (for example, ref. 9). The tools we have for human studies—electroencephalography, magnetoencephalography and fMRI—are good for large-scale recording and, with high-density fMRI, are becoming good for fine spatial scales too. However, they not good enough alone. Notably, they are each dominated by the synaptic signals, and so they nicely complement techniques such as extracellular recording by providing a measure, albeit a complex one, of the input signals to each cortical area. In conclusion, Picard *et al.*[3] have demonstrated that one effect of long-term practice in a motor task is to alter synaptic efficacies. We can expect similar changes in the human cortex: 10,000 h may allow a skilled pianist to evoke motor cortical outputs controlling finger movements with quite modest incoming signals and, perhaps, with relatively little mental effort.

## COMPETING FINANCIAL INTERESTS

The author declares no competing financial interests.

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