

Skill learning: **Bringing cognition to its senses**

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The brain areas involved in a task may change their contribution as one acquires expertise. An understanding of how this occurs relies on a good psychological theory of the processing requirements of a task and knowledge of which regions of the brain can perform the necessary component computations.

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Current Biology 1998, 8:R572–R574
<http://biomednet.com/elecref/09609822008R0572>

© Current Biology Publications ISSN 0960-9822

Practice makes perfect. This much we all agree upon. What it is that learns, or precisely what is learned are different matters. Consider learning to play the trumpet. As you improve, your fingers become quicker and more accurate at pressing the correct combination of valves, your breathing becomes more efficient and your interpretation of a piece becomes more musical. How would you account for these improvements in terms of brain areas? Would you propose that a master learning area coordinates breathing, motor coordination and musical appreciation? Are the improvements of your fingers, your diaphragm and your musical sense represented entirely independently? Must one kind of improvement occur before another type is possible?

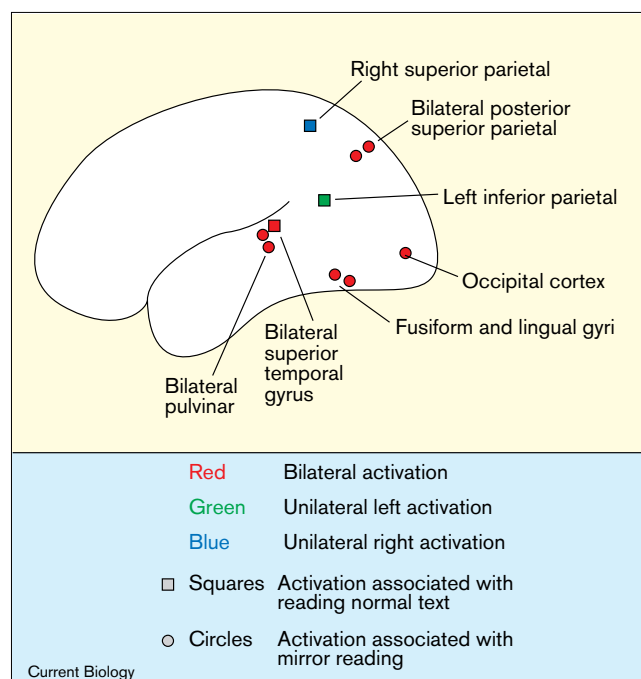
These kinds of questions have been amongst the most difficult to address by classical neuropsychological methods, either because patients with brain damage may learn new skills in abnormal ways or because they may not show appreciable learning at all. One of the advantages of the brain mapping techniques now available is that normal subjects can be scanned, stimulated or recorded repeatedly over the course of days, weeks or months as they acquire a new skill. It is therefore now possible to track changes in cortical organisation during learning, and this approach is beginning to bear interesting fruit.

Psychophysical studies of perceptual skill learning have demonstrated conclusively that cortical plasticity continues into adult life and is not limited to early childhood [1]. These studies also suggest that one learns with a high degree of stimulus specificity [2–4] and without generalisation to other, similar tasks. For example, if one learns to search through, detect or discriminate a particular group of colours on a computer screen 50 centimetres away, one's improved performance will not be maintained if the screen is moved another metre away or the colours are

changed. In view of this specificity, one might imagine that brain activation studies would show that the learning of a new perceptual skill involves 'low level' sensory areas, rather than regions associated with strategy management. Surprisingly few brain imaging studies [5,6] have addressed the issue of perceptual learning — perhaps because it requires a specific hypothesis about how a task is performed — but a recent study [7] provides a good example of how to tackle this important problem.

Poldrack *et al.* [7] scanned subjects, using functional magnetic resonance imaging (fMRI), at two stages of learning to read mirror-reversed words: not a task that comes *υλιεε* to most readers. First, subjects were scanned while reading either mirror-reversed or plain text words. They were then given 1080 trials, over three sessions, to practice mirror reading and were then scanned again in three different conditions in which they viewed either previously unseen mirror-reversed words, the mirror words on which

Figure 1



Brain regions activated in the Poldrack *et al.* [7] study, as determined by fMRI, when subjects read normal text (squares) or mirror-reversed words (circles). Red, bilateral activation; blue, unilateral right hemisphere activation; green, unilateral left hemisphere activation. It is clear that normal text activated fewer posterior sites, and that the activity was more lateralised than in the case of reading mirror-reversed words.

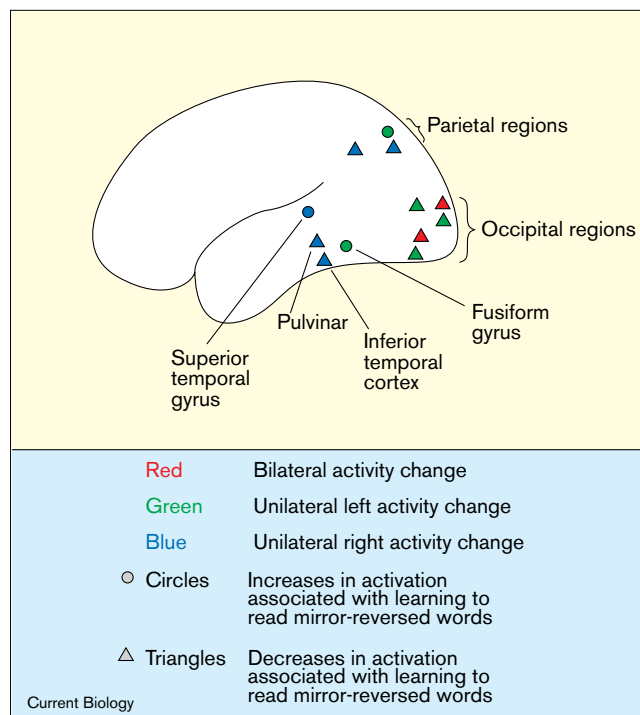
they had practised or plain text words. The authors based their study on two clear predictions. First, they argued that learning to read mirror-reversed words required “substantial visuospatial transforms”, by which they mean something akin to mentally rotating a mental image of the stimulus, and second, that “the visual skill learning involves a progression from visuospatial transformation to object recognition”. The brain regions likely to be involved in these aspects of the task are well documented: the parietal cortex is crucial for visuospatial transformations, and in particular for the perception of rotated and reflected shapes [8]. Regions of the temporal lobe, on the other hand, are necessary for object recognition.

The results of the first stage of fMRI scanning, before learning, are shown in Figure 1. As predicted, reading mirror words was associated with increased activity in the posterior superior parietal lobule and intraparietal sulcus, areas which have been shown to be important for visuospatial tasks in other imaging and magnetic stimulation studies [9,10]. Mirror reading was also associated with activation of parts of the occipital lobe and the fusiform and lingual gyri. Other areas activated included the pulvinar and the cerebellum. The activations associated with reading normal words were in agreement with previous studies [11]: increases in activation were seen in the left inferior parietal lobule, the right anterior superior parietal cortex and the superior temporal gyrus. Mirror reading clearly requires more posterior parietal and posterior temporal involvement than does normal reading.

The crucial question is what happens as a consequence of learning? Let us imagine that the authors are correct in their assumption that, when reading mirror-reversed words, the subjects have to spatially rotate or transform a mental image of the stimulus. Perhaps subjects simply become more efficient at mental rotation with practice, in which case parietal activation would remain constant or perhaps increase. This would indicate that one maintained the same strategy during learning. Furthermore, if the subjects were to become more efficient at mental rotation, then one would not expect changes in the temporal lobe activations associated with object recognition. What Poldrack *et al.* [7] actually found was more interesting than these possibilities. Following training, the subjects were indeed more efficient at the task — more accurate and faster — but the changes in cerebral activation (Figure 2) suggest that the subjects did not become ‘super mental rotators’. Rather, they formed a new representation of mirror-reversed words.

In support of this idea, Poldrack *et al.* [7] found a decrease in activation of the right superior parietal lobule, presumed to reflect a decrease in the spatial strategy required, and an increase in activation in the left inferior temporal cortex, presumed to reflect the formation of a new representation.

Figure 2



Increases and decreases in the activations associated with learning to read mirror-reversed words, determined by fMRI. Red, bilateral activation change; blue, unilateral right hemisphere activation change; green, unilateral left hemisphere activation change. The pattern shows a shift to lateralised activity, as opposed to the bilateral activity seen in Figure 1. There were decreases in activity (triangles) as a consequence of learning.

Accompanying the left inferior temporal activity was a decrease in more posterior occipital activity. A colleague and I have suggested elsewhere [8] that mental rotation strategies may require access to simple features of an object, and that the object is not transformed as a whole but piecemeal, feature by feature. It is possible, therefore, that the shift from posterior visual cortex activation (pre-learning) to inferior temporal activation (post-learning) represents a change from reliance on simple features to the use of whole objects, in this case words.

Using transcranial magnetic stimulation (TMS) to study the role of parietal cortex in perceptual learning, my colleagues and I [10] recently obtained results that corroborate the findings of Poldrack *et al.* [7]. Magnetic stimulation applied over right posterior parietal cortex 100 milliseconds after the onset of a visual array impaired performance on a visuospatial search task when subjects were naive, but not when they had been trained on the task. Improved performance in the visuospatial task through learning did not transfer to another, similar task, and there was no suggestion that the critical time for applying TMS became any

earlier as subjects became practised. As in the work of Poldrack *et al.* [7], then, there is no evidence that learning a visuospatial task results in becoming more efficient at visuospatial manipulations. Rather, as Poldrack *et al.* [7] suggest, the improvement seems to require the acquisition of a new object representation.

Poldrack *et al.* [7] investigated the consequences of training a little deeper by comparing the brain regions involved in reading mirror-reversed words on which the subjects had trained with those active when the subjects were required to read new mirror-reversed words. Behaviourally, there was no evidence of transfer of learning to the new mirror-reversed words — as in so many experiments, the skill acquisition was specific to the training stimuli. The imaging results showed that, during the reading of familiar mirror-reversed words, there was less activation in several areas of the brain than was seen during the reading of new mirror-reversed words. These areas included the superior parietal cortex and intraparietal sulcus, as well as occipital cortex and fusiform and lingual gyri.

These findings are intriguing, but it is difficult to agree entirely with the conclusion drawn by the authors from this particular aspect of the experiment. Although Poldrack *et al.* [7] argue that the reductions demonstrate “priming-related reductions in activity for task-related regions”, one wonders whether a delay period of days is closer to memory than short-term priming. Perhaps a more parsimonious explanation, which the authors also proffer and earmark for future investigation, is that subjects make fewer eye movements on practiced, relative to unpracticed, mirror reversals. What the differences between practiced and unpracticed mirror words do demonstrate, however, is that it is possible to track cortical reorganization at different stages of learning. As Poldrack *et al.* [7] note, “the priming-related [or memory related?] reductions [were observed] in a region that was not initially involved in task performance but became involved as skill learning progressed”.

This work has several important implications. It would not be a great step to modify the paradigm used by Poldrack *et al.* [7] to look for changes in cortical involvement as a function of task difficulty [12], and to compare the type of cortical plasticity found in the adult brain with that observed in early life [13]. Much of our activity in daily life is skillful, and it is important to be able to understand the brain mechanisms underlying skilled behaviour; to do otherwise may result in a neurobiology of, and for, the naive.

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