memory. In the repeated subtraction task, for instance, subjects had constantly to keep in mind the number that they had reached and update it after each subtraction. This important memory load likely explains the involvement of prefrontal circuits in this task.

Dehaene, Stanislas
The Number Sense

When the Brain Multiplies or Compares

Roland and Friberg's experiment probed only a single complex arithmetical task, with the aim of identifying the areas involved in arithmetic. This was just a first step. Neuropsychological dissociations lead us to expect a much finer-grained fragmentation of cerebral areas. Depending on the requested arithmetic operation, very different cerebral networks should activate. To begin to evaluate this hypothesis, my colleagues and I recently examined how cerebral activity changes in the course of number comparison and multiplication.

The experiment was performed in Orsay at a medical research center well equipped for measuring cerebral metabolism. Eight medical students served as volunteers. Upon their arrival at the hospital in the morning, high-resolution magnetic resonance anatomical images of their brains were made. Later in the afternoon, positron emission tomography provided us with the first detailed images of the areas that were activated while they processed numbers.

Remember Mr. N, the patient who could not multiply but could still tell which of two numbers was larger? The goal of our study was to investigate whether the neuronal circuits involved in multiplication and comparison did partially rest on distinct brain areas, as we had postulated based on Mr. N's results. We thus presented subjects with a series of pairs of digits that they either had to compare or multiply mentally. In both cases, the result of the operation—either the larger of the two digits or their product—had to be named covertly, without actually moving the lips. Cerebral blood flow during those two tasks was contrasted to a third measure obtained while the subjects were at rest.

As we expected, several brain regions were equally active during multiplication and during comparison relative to the rest period. These regions most probably support functions common to both tasks, such as extracting visual information (occipital cortex), or maintaining gaze fixation and the internal simulation of speech production (supplementary motor area and precentral cortex).

The inferior parietal cortex, so crucial to quantitative number sense, was also active. Oddly, it was intensely active in both hemispheres during multiplication, while its activity during comparison was small and on the verge of being inde-

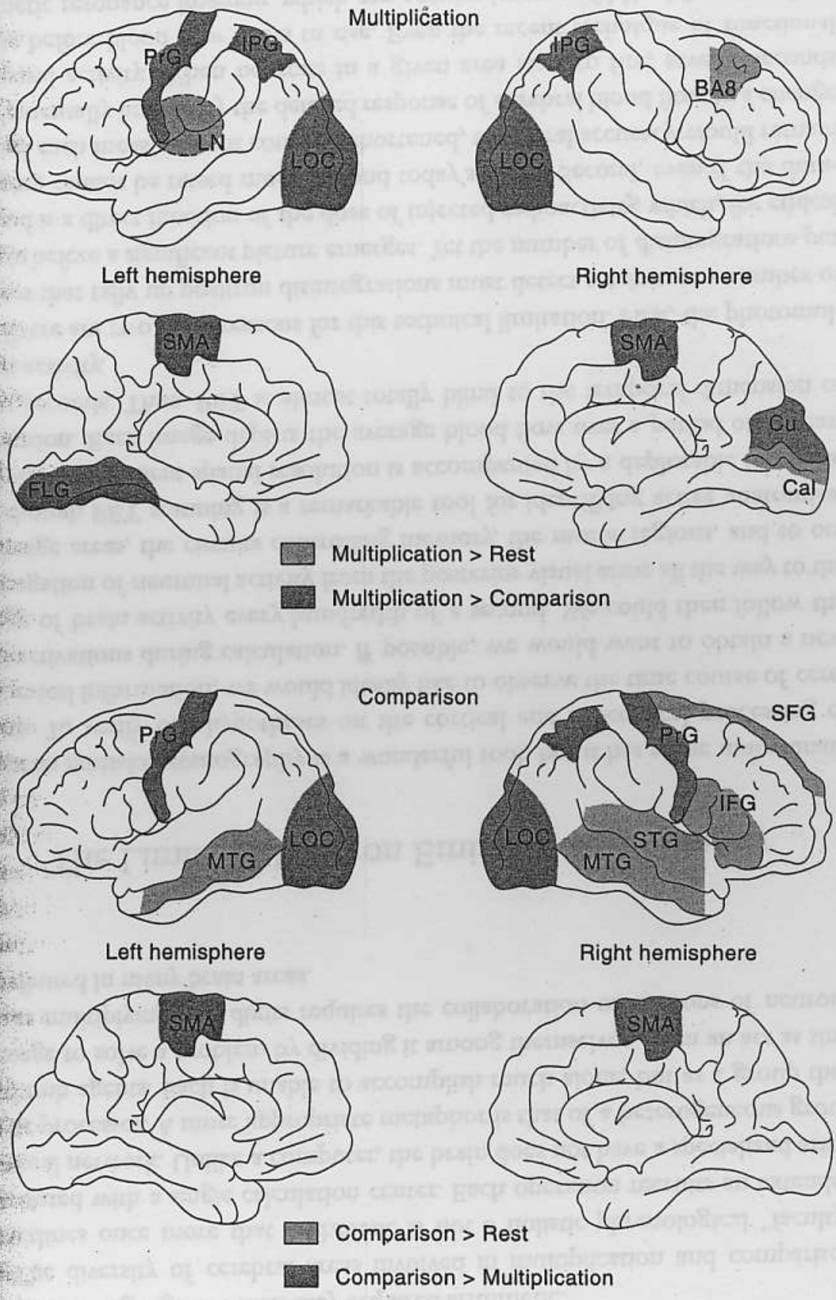

Figure 8.4. Positron emission tomography reveals wide networks of cerebral areas whose blood flow changes when subjects rest with their eyes closed, multiply pairs of Arabic digits, or compare the very same digits. (After Dehaene et al. 1996.)

0125-1

tectable. We had expected the reverse: Comparison calls for the processing of numerical quantities, and simple multiplication requires only access to verbal memory. However, not all the multiplication problems we used were simple. The list included problems such as 8×9 or 7×6 on which our subjects often hesitated or failed altogether. Since their verbal memory for arithmetic facts seemed unreliable, we speculate that they were often forced to resort to backup strategies heavily dependent on the inferior parietal cortex to provide a plausible answer. Conversely, the number comparison task we used was probably too easy becausee the numbers ranged only from 1 to 9. Finding the larger digit may have been too simple to stimulate intense inferior parietal activation. Perhaps we also left the subjects too much time to respond, which may have diluted the activations to the point of rendering them too small to detect. At any rate, inferior parietal cortex seemed to activate in direct proportion to the difficulty of the numerical tasks that the subjects performed.

The most interesting results emerged, however, when we directly contrasted number comparison with multiplication. Several temporal, frontal and parietal regions showed a notable shift in hemispheric asymmetries. During multiplication, cerebral activity was more intense in the left hemisphere, but during comparison it was equally distributed across the two hemispheres or even shifted to the right. This observation is in agreement with the notion that multiplication, but not comparison, rests in part on the language abilities of the left hemisphere. Contrary to multiplication, number comparison does not have to be learned by rote. A mental representation of number magnitude emerges without explicit teaching in young children and even in animals. Hence, the brain does not need to convert digits to a verbal format in order to compare them. Functional brain imaging confirms that the comparison of numerical magnitudes is a nonlinguistic activity that rests at least as much on the right hemisphere as on the left. Each hemisphere can recognize digits and translate them into a mental representation of quantities to compare them.

A subcortical nucleus, the left lenticular nucleus, was also more active during multiplication than during comparison. We know from Chapter 7 that a lesion in this area can dramatically impair memory for multiplication facts and other verbal automatisms. Remember Mrs. B, who had forgotten how to recite "three times nine is twenty-seven," the alphabet, and the Our Father? Her lesion was right in this area. The lenticular nucleus belongs to the basal ganglia, which are generally thought to contribute to the routine aspects of motor behavior. Functional brain imaging suggests that they also contribute to more elaborate cognitive functions. Perhaps arithmetic tables are stored in the form of automatic word sequences, so that recalling them becomes mechanical. Reciting the multiplication table at school may imprint every word of it in our deep brain structures. This would explain why even the most fluent bilinguals still prefer to calculate in the language in which they acquired arithmetic.

The diversity of cerebral areas involved in multiplication and comparison underlines once more that arithmetic is not a holistic phrenological "faculty" associated with a single calculation center. Each operation recruits an extended cerebral network. Unlike a computer, the brain does not have a specialized arithmetic processor. A more appropriate metaphor is that of a heterogeneous group of dumb agents. Each is unable to accomplish much alone, but as a group they manage to solve a problem by dividing it among themselves. Even an act as simple as multiplying two digits requires the collaboration of millions of neurons distributed in many brain areas.

The Limits of Positron Emission Tomography

Positron emission tomography is a wonderful tool, but it has some unfortunate limits. To verify our hypotheses on the cortical and subcortical processing of numerical information, we would ideally like to observe the time course of cerebral activations during calculation. If possible, we would want to obtain a new image of brain activity every hundredth of a second. We could then follow the propagation of neuronal activity from the posterior visual areas all the way to the language areas, the circuits controlling memory, the motor regions, and so on. Yet though PET scanning is a remarkable tool for identifying active anatomical regions, its excellent spatial resolution is accompanied by a deplorable temporal resolution. Each image depicts the average blood flow over a period of at least forty seconds. Thus, PET is almost totally blind to the temporal dimension of brain activity.

There are two main reasons for this technical limitation. First, the photomultipliers that tally up positron disintegrations must detect a minimum number of events before a significant picture emerges. Yet the number of disintegrations per second is a direct function of the dose of injected radioactivity, which, for ethical reasons, cannot be raised much beyond today's limits. Second, even if the duration of each measurement could be shortened, temporal accuracy would remain fundamentally limited by the delayed response of cerebral blood flow to a change in neural activity. When neurons in a given area start to fire, several seconds elapse before blood flow starts to rise. Even the recent technique of functional magnetic resonance imaging, which can acquire images of blood flow in a fraction of a second, suffers to a similar extent from the slowness of blood flow responses.

0125-2