Brain Literacy for Educators and Psychologists

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notation system for numbers is a kind of visible language with place value as its syntax. A longitudinal study showed that neuropsychological measures of hand function predict children's arithmetic skills early in formal schooling (Fayol, Barrouillet & Marinthe 1998). This relationship makes sense given that the hand plays an important role in this external representation system for producing visual notation of number concepts. Accordingly, the hand plays a major role in learning basic arithmetic facts and operations, which are often expressed in writing (see arithmetic module in Figure 7.1).

Crosstalk between the Quantitative and Visual-Spatial Systems

The Computing Brain develops crosstalk with the visual system—with both (a) the sensory features of the incoming visual stimuli and (b) the abstract visual-spatial representations of the physical world that the developing child is acquiring. From this wedding of two representational systems—for quantitative information and for abstract visual-spatial understanding—develops children's geometric knowledge of the world; see Figure 7.1. The quantitative representations inform the visual-spatial understandings and the visual-spatial understandings inform the quantitative representations. This crosstalk creates the conceptual foundations for some kinds of scientific knowledge such as physics (Greene 1999). This communication link also provides a potential instructional tool that capitalizes on the multiple representations of the Computing Brain in teaching math, as is discussed in Chapter 10.

Computing Brain at Work

The Computing Brain is fundamentally a problem-solving brain, much as the Writing Brain is. However, it has different kinds of problems to solve. Working memory is critical to this problem-solving effort. From the beginning of true counting, the problem solving space in the conscious part of working memory is put to work. When the problems are fairly simple, they can be solved using internal mental representations. When the problems exceed the capability of working memory, concrete aids in the external environment may be needed, for example, a number line that the brain can see and the hand can touch while counting. Other peripheral aids may also help, such as paper and pencil written computations that use a visual notation system to represent quantity, quantitative relationships, and arithmetic operations. Once basic arithmetic is mastered and the mathematical problems become even more complex, a hand-held calculator may be used to perform the arithmetic operations even more quickly, thus overcoming some of the temporal constraints in the capacity-limited workspace for problem solving. However, a calculator cannot compensate for lack of mental representations of number lines and the part-whole concept that are necessary for high-level problem solving. Software that provides computer-generated visual representation of numerical concepts may facilitate high-level problem solving, but research is needed on this topic.

IN VIVO FUNCTIONAL IMAGING STUDIES OF MATH

To date, functional imaging has been used to study mostly quantitative estimation and computational functions of the brain. For example, in one of the early studies in this field, Dehaene and Cohen (1995) reported that procedural knowledge for arithmetic facts may involve the lenticular nucleus. One goal of many of these studies has been to tease apart how numbers are represented differently in the brain depending on whether visual codes (digits), verbal codes (names), or quantitative codes (distributed along an internal number line in analog fashion) are involved. Another goal has been to tease apart stored representations (e.g., math facts) from operations (e.g., applying computational algorithms). The following studies are representative of the recent studies that have employed ERP, fMRI, and PET technologies.

In one ERP study, Dehaene (1996) asked participants to classify numbers as to whether they were larger or smaller than a target number. He varied whether the target number was an arabic numeral (5), which is a visual notation for the number, or an English word (five), which is a phonological code for the number. These codes also differ as to whether they have underlying continuous representations (arabic numerals) or underlying categorical representation (names). The N1 ERP component (a negative amplitude that peaks about 100 milliseconds after stimulus onset) was symmetrical for the digits but was left lateralized for number names. Thus, number meaning may be accessed differently in the brain depending on the code used to represent the concept of number or the nature of the underlying representation—analog or digital. In a second ERP study, Iguchi and Hashimoto (2000) administered three tasks: adding presented digits, counting presented digits, and counting the number of meaningless patterns. Within the first 300 milliseconds, physical and numerical attributes of the stimulus were identified, but calculation (a procedural computational operation) occurred over a larger time course and was associated with a positive, slow potential, which was probably related to accessing stored knowledge in memory.

PET technology has been used to study both addition and multiplication. In one study (Pesenti, Thioux, Seron & DeVolder 2000) four tasks were completed: rest with eyes closed; physical judgment of whether digits or nonnumerical characters were arabic numerals; addition of the same digits as used in the physical judgment task; and comparison of which number in the same pairs was larger. The comparison task activated the right superior parietal lobe, whereas the addition task activated right orbital frontal and right anterior insula. Orbital frontal and insula regions are involved in automatic retrieval in other domains (see Chapter 3); thus, it is plausible that they may also be activated in automatic retrieval of math facts and application of algorithms to addition, both of which are well practiced in normal adults. Both tasks activated a left frontal parietal network including intraparietal sulcus, superior parietal lobule, and precentral gyrus. These results differed from those reported by Dehaene and Cohen (1995) in support of a Triple Code Model, in which arabic numerals are processed bilaterally in occipital-temporal regions, magnitude is represented in parietal lobes, and retrieval of math facts occurs in left language areas and left subcortical areas (see Figures 3.4, 5.1, and 5.4). Thus, as was the case with language (see Chapter 5), neuroanatomical location may vary with slight differences in tasks that affect attention and working memory load. Nevertheless, the accumulating evidence from these and other studies indicates that there is not a single computational center in the brain.

In another PET study, Dehaene et al. (1996) compared a multiplication task (quantitative operation) to a number comparison task (quantitative representation). For the multiplication task, instructions were to carry out a mental multiplication of two digits and name the answer silently inside the head. For the comparison task, instructions were to decide which of two digits (same pairs as used for multiplication) was larger. Both tasks had common activations, compared to a rest (with eyes closed) condition, in lateral occipital cortex bilaterally, left precentral gyrus, and supplementary motor area (see Figures 3.4, 5.4, and 6.4). This finding suggests that, even with eyes closed, visual codes are imaged, and that even when written computation is not involved, the brain is in a state of readiness for writing. The number comparison task uniquely activated the right superior temporal gyrus, left and right middle temporal gyri, right superior frontal gyrus, and right inferior frontal gyrus. The multiplication task uniquely activated inferior parietal gyri bilaterally, left fusiform and lingual gyri, right cuneus, left lenticular nucleus, and BA 8; see Figure 7.3. The authors concluded that magnitude estimation along an analog number line and arithmetic algorithms have partially distinct neural networks.

fMRI studies have also added to our understanding of the computing brain. In an event-related fMRI study, which provides temporal and spatial information, Pinel, Le Clec'H, van de Moortele, Naccache, Le Bihan, and Dehaene (1999) focused on differences in digit and number word representations, as had been done in past studies. Digits uniquely activated right fusiform gyrus (see Figure 5.2) and left precentral gyrus (see Figure 5.4), whereas number words uniquely activated left inferior parietal lobule and right postcentral/inferior parietal regions (see Figure 5.1). This study lent further evidence that numerical information is stored in different kinds of codes in the brain.

Dehaene, Spelke, Pinel, Stanescu, and Tsivkin (1999) used fMRI to compare exact arithmetic and estimated arithmetic. Exact arithmetic recruits stored information and procedures that are language-based, whereas estimated arithmetic recruits nonlanguage based quantitative representations. For example, an exact

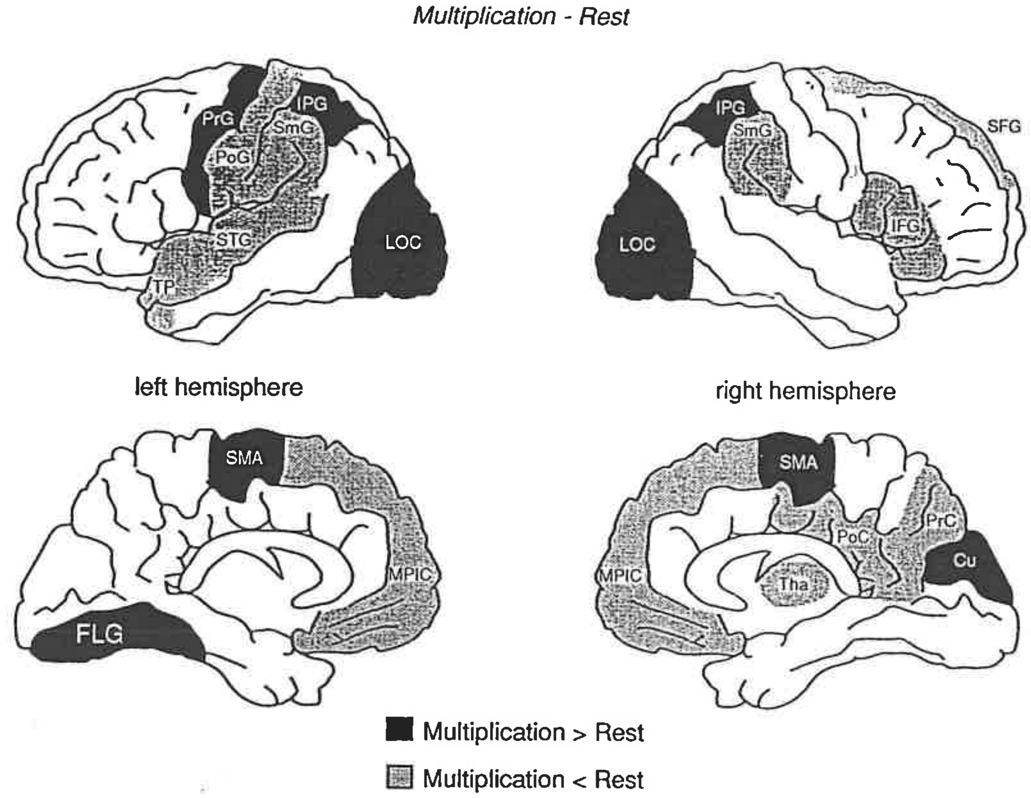

FIGURE 7.3 Regions significantly activated or deactivated during multiplication relative to rest. (Lateral and mesial views of hemispheres). LOC = lateral occipital lobe. SMA=supplementary motor areas. PoG = postcentral gyrus. SmG = Supramarginal gyrus. IFG = inferior frontal gyrus. Tha=thalamus. STG = superior temporal gyrus. Cu = cuneus. FLG = fusiform and lingual gyri. IPG = inferior parietal gyrus. PrC = precuneus. TP = temporal pole. SFG = superior frontal gyrus. MPfc = medial prefrontal cortex. PoC = posterior cingulate gyrus. Reprinted from *Neuropsychologia*, vol 34, Dehaene, Tzourio, Frak, Raynaud, Cohen, Mehler, and Mazoyer, page 1101, Copyright 1996, with permission from Elsevier Science.

arithmetic problem required selection of a correct answer (4 + 5 = 9? or 7?), but an estimated arithmetic problem required an approximate answer to the same problem (4 + 5 = 8? or 3?). The approximate task activated parietal lobes bilaterally more than the exact test did, suggesting that the parietal lobes are part of a quantitative circuit. The investigators concluded that there are two main components of calculation circuits—left inferior frontal for exact arithmetic and bilateral intraparietal for approximate arithmetic (estimation).

Burbaud, Camus, Guehl, Bioulac, Caillé, and Allard (1999) used fMRI to investigate mental subtraction. Medical students performed two tasks: covert number production with calculation and covert number production without calculation. For the first task, instructions were to think of a three-digit number greater than 500, subtract a prime number (13 or 17) from it, and repeat the process. For the second task, the instructions were to think of a three-digit number greater than 500. The first task activated left dorsolateral prefrontal and premotor cortices, Broca's area, and inferior parietal cortex bilaterally. The second task activated Broca's area and left premotor and prefrontal cortex , and hardly any left inferior parietal cortex when calculation was not involved (see Figures 3.4, 5.1, and 6.6). The investigators concluded that mental subtraction may involve a distributed system including left dorsolateral prefrontal cortex (DLPFC) and inferior parietal cortex bilaterally.

Rickard, Romero, Basso, Wharton, Flitman, and Grafman (2000) used fMRI to compare three tasks: simple arithmetic, numerical magnitude estimation, and perceptual-motor control. In the first task, college students verified a multiplication fact (e.g., 4 × 7 = 35, true? or false?). In the second task, they performed a numerical magnitude judgment (which is larger 24? or 25?). In the third task, they decided if a 1 was present in a 4-digit string. Compared to the other tasks, the multiplication task uniquely activated BA 44 and parietal cortex bilaterally but greater on the left, but the magnitude estimation task uniquely activated inferior parietal cortex bilaterally (see Figures 3.1 and 3.2).

Fullbright, Molfese, Stevens, Skudlarski, Lacadie, and Gore (2000) compared three tasks: matching, multiplication, and a control. For each task, three or four single digit or low value double-digit numbers were presented serially; the target stimulus appeared after a 12-second delay. For matching, instructions were to decide if the target stimulus matched the previously presented stimulus. For multiplication, the task was to decide if the target stimulus was the product of previous numbers. For the control task, the numbers were always zeroes. Left-middle frontal gyrus (see Figure 5.1) and left frontal lobes activated more on multiplication than matching. These results differ from Burbaud et al. (1999) but are consistent with the investigators' conclusion that quantitative processing is dependent on both language and nonlanguage representations.

Taken together, these results show that many of the same brain areas are activated by the functional math system as for the functional reading and writing systems. At the same time, some brain areas are uniquely activated for the functional math system. The results as to which brain regions are activated for a particular imaging task were not always consistent across studies, possibly because specific tasks activate only part of a circuit. It is important to remember that a single brain locus most likely does not support a single component of any brain system—rather a neural circuit distributed across brain sites does. Nevertheless, the parietal areas appear to be a component of many of the neural circuits of the Computing Brain.

BUILDING A COMPUTING BRAIN

Table 7.1 summarizes the wetware components of a functional math brain and their possible locations, given results of current brain imaging studies. The newly constructed components of this brain system are the quantitative component, the arithmetic module with stored math facts and computational algorithms, the visual notation system for number, the visual-spatial system that represents geometric information about the physical world, a grapho-motor component for writing the

TABLE 7.1 Constructing the Wetware for a Computing Brain

Function[a]	Possible brain Structure(s)[b]
Arousal unit	Reticular activating system (RAS) and its cortical connections
Quantitative Knowledge[d]	
Number concept (quantity)	
Counting (1–1 correspondence)	
Number line/analog representation of number	Right superior parietal lobe; inferior parietal cortex bilaterally; parietal lobes bilaterally; right superior temporal gyrus; middle temporal gyrus bilaterally; right superior frontal gyrus; right inferior frontal gyrus; left frontal parietal network; occipital cortex bilaterally; supplementary motor area; left precentral gyrus; Broca's area; left premotor; left prefrontal cortex
Place value	Unknown
Part-whole relationships	Unknown
Multivariate relationships	Unknown
Arithmetic Module[d]	
Math facts	Lenticular nucleus; left language and subcortical areas
Computational algorithms	Left inferior frontal and parietal areas
addition	Right orbital frontal; right insula; left frontal parietal network; left inferior frontal area
subtraction	Left dorsolateral prefrontal; inferior parietal bilaterally; left premotor; Broca's area
multiplication	Inferior parietal gyri bilaterally; parietal bilaterally; left fusiform and lingual gyri; right cuneus; left lenticular nucleus; BA 8; BA 44; left middle and frontal gyri; left frontal parietal network; occipital cortex bilaterally; supplementary motor area; left precentral gyrus
Visual-Spatial System[d]	
Sensory input	See Table 3.2 for primary projection pathway
Extraction of visual features (nonlinguistic)	V1 striatal cortex/striatal cortex
Visual Notation System[d] for representing number in numerals	Right fusiform gyrus; bilateral occipital-temporal areas; left fusiform and precentral gyri; right precentral and inferior parietal regions
Ventral *what* pathway for objects (identity of small elements in linear array)	Occipital to temporal cortex
Dorsal *where* pathway for objects (spatial relationships of small elements in linear array)	Occipital to parietal cortex
Geometrical[d] (visual-spatial)	Unknown

(*continues*)

TABLE 7.1 *(continued)*

Grapho-Motor Component[d]	See Table 6.2
Linguistic Representations of Mathematical Problems — draws on Aural Language System[c]	See Table 5.4
Math Lexicon[d]	
Quantitative vocabulary	Left inferior parietal lobule; right precentral/inferior parietal regions
Visual-spatial vocabulary	Unknown
Arithmetic operations vocabulary	Unknown
Other vocabulary knowledge	Unknown
Executive/Government System	Prefrontal cortex (especially left dorsal; prefrontal cortex, LDPFC)
Cross-talk between existing systems in constructing new system	
Cross-talk with reading brain in solving word problems	See Table 5.4
Working with attentional system (focus, maintenance, transitions)	
Creating goals and plans	
Coordinating multiple operations	
Control processes for working memory	
Metacognition (reflection) about math	
Memory	
Working memory	
Phonological STM	See Tables 5.3, 5.4
Visual-Spatial STM	See Table 5.3
Central Executive(s)	Prefrontal cortex
Long-Term Storage	See Table 5.3
Implicit (Unconscious) Network — automatically activated (primed) math facts	Unknown
Explicit (Conscious) Semantic Retrieval	Temporal cortex; left hippocampus
Attentional System	See Table 5.4
Cognition	
General Reasoning	Lateral frontal network
Quantitative	Unknown
Visual-Spatial	Unknown
Verbal	Unknown

(continues)

TABLE 7.1 *(continued)*

Emotions and Motivation	Limbic structures—amygdala, septum; hypothalamus—and their cortical connections
Learning Circuits	See Table 5.4
Controlled processing—Learning facts and algorithms	Unknown
Automatic processing—Automatic retrieval of facts and algorithm application	Right cerebellum; right orbital; insula

[a] See section at end of Chapter 7 for description of function.

[b] Based on existing research reviewed in Chapters 3, 4, and 5. however, research evidence is not always consistent and future research may modify or extend current understanding of structure-function relationships.

[c] Based on research evidence for processing aural language; refers to knowledge that is stored in long term memory at different levels of language.

[d] Unique to the newly constructed math computing system.

visual notation system, and a specialized math lexicon. This lexicon of single words and phrases is specialized for quantitative concepts (e.g., greater than or less than), visual-spatial concepts (e.g., above, between, diagonal, circumference), and arithmetic operations (e.g., How much altogether? How much more? How many will each have?).

As with reading and writing, the Computing Brain must be awake and sufficiently aroused to process incoming information from the environment and conduct ongoing processing within the internal mental environment. Separate representations for arithmetic facts (e.g., sums of 1-digit numbers, removal of 1-digit numbers, repeated sums of 1-digit numbers, and repeated removal of 1-digit numbers) and algorithms for operating on these facts are stored in separate, but possibly partially overlapping circuits, in long-term memory. Quantitative knowledge is represented in continuous, analog fashion along a number line. Visual symbols for representing this quantitative knowledge and grapho-motor procedures for writing these visual symbols are also stored in long-term memory. Procedures for representing and manipulating part-whole relationships are established. More than one internal number line may be created for purposes of accessing multiple dimensions in problem solving. Computing Brains show individual differences in how quickly and easily they establish these internal representations of number lines and part-whole relationships.

The Computing Brain keeps the executive/government system very busy. To begin with, the Computing Brain recruits the Reading Brain during written math word problem solving and the Writing Brain during written computation. During problem solving, the Computing Brain recruits the executive system to create goals and plans, coordinate multiple operations, monitor ongoing processes, and exert executive control over the working memory system. The executive system also