Chapter 7

The Exographic Revolution: Neuropsychological Sequelae

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Objects, manufactured or not, are ubiquitous in human cultural life and play an important role in our mental lives. Biologically modern humans have always been surrounded by meaningful objects, which can point, remind, entrench, signify and sustain the patterns of social custom and thought. They, and material culture in the wider sense, frame the ideas and routines that drive everyday life. They can be said to have cognitive 'lives' inasmuch as they enter into mind, solidify and channel shared experience and define the social order. But, to a degree, objects can also signify things to apes, monkeys, dogs, bears and cats. Objects remind them of past events, point toward certain patterns of action, entrench habits and define routines. Put into traditional terminology, objects are transformed into conditioned stimuli through association, and, in this behaviouristic guise, their cognitive role does not stand out as uniquely human.

However, there is a way in which certain manufactured objects serve the human species in a unique, and evolutionarily novel, manner. I am referring to a class of manufactured objects that are sometimes called 'symbolic technologies'. These are specifically designed to represent, communicate and store knowledge. Such objects introduce a completely new element into human cognition: external, that is, non-biological, memory storage (as in an encyclopaedia, for example). Non-biological memory media enable us to record and display complex ideas in highly accessible formats that are easy to revise and refine. The introduction of radically new memory media into the cognitive system of the human species has transformed the way human beings carry out their cognitive business, both individually and collectively.

Memory media: engrams and exograms

Lashley (1950) called a memory record stored inside the nervous system an 'engram'. There are at least five dissociable engram, or memory, systems in the human brain. The five systems include (1) *motor skills*, for example, writing, or driving; (2) *conditioned emotional responses*, for example, a state of anxiety triggered by the sight of a rival; (3) *perceptual learning*, for example, learning how to distinguish various subtypes of a certain class, say, flowers or faces; (4) *semantic memories*, which tend to be abstract generalities encoded in language; and (5) *episodic memories* of personal experiences, which are highly specific, detailed and vivid. These five categories have been established for some time in experimental research, and, although there are still controversies about their neuro-chemical foundation, these are very likely to stand as functionally distinct subsystems from a cognitive standpoint.

Neuropsychological studies of memory disorders, or amnesias, have shown that these different memory systems can break down independently of one another; for example, it is common to lose episodic, but not semantic memory, in amnesia (Tulving 1985). There is also evidence from brain-imaging research and clinical case studies that these types of memory depend on anatomically distinct brain networks. In addition, they have different storage and retrieval characteristics; for example, new skills are learned gradually through repetition and practice, whereas vivid episodic memories are usually acquired in a single trial. Some of these memory systems — most notably semantic memories — are special to humans, while others are shared with many other species (Tulving 1985). At a minimum, we must conclude that there are several kinds of engrams, which are learned and stored in various neural subsystems.

Memory records stored outside the nervous system (for example, clay tablets, papyri, printed books, government archives or electronic data banks) can be called 'exograms' (Donald 1991; 1998). Exograms take many forms (Table 7.1).

From present archaeological evidence, simple exograms were invented by biologically modern humans in the late Upper Palaeolithic. They took the form of significant objects that had been pierced, carved or painted. Over a very long period of time, and after

Table 7.1. *Examples of generic exogram systems, in rough order of emergence.*

Significant objects, amulets, totems, masks, magical tokens
Transient and permanent iconography (in sand, mud, stone)
Crafted mnemonic devices, such as knotted cords
The built environment
Painted and sculpted images, such as cave paintings and totems
Astronomical measuring devices, such as stone circles and burial mounds
Trading tokens
Early scripts for trade and crop administration
Longer written records of crops, laws, edicts, genealogies
Works of literature, poetry
Mathematical and geometrical notations
Architectural and engineering drawings, models
Libraries and archives
Elaborate scientific and navigational instruments
Moving pictures, computers, electronic media
'Smart' machines, robots, high-technology virtual environments

Table 7.2. *Some properties of engrams and exograms (modified from Donald 1998).*

Internal memory record (engram)	External memory record (exogram)
Fixed physiological memory systems	Unlimited number of physical media
Constrained format, depending on type of record, and cannot be reformatted	Unconstrained formats, and may be reformatted
Impermanent, dies with subject	Quasi-permanent; exceeds life-span
Limited capacity, single entries quite small (e.g. words, names, images, narratives)	Unlimited capacity; entries may be very large (e.g. novels, encyclopaedias, reports; legal systems)
Highly vulnerable to unintended distortion, deterioration, degradation	Much less vulnerable to unintended distortion
Main cues for recall are proximity, similarity, meaning	Retrieval paths unconstrained; novel options such as cataloguing, indexing
Limited perceptual access to engrams in audition, very limited and unreliable access to visual engrams	Theoretically unlimited direct perceptual access to exographic records with various kinds of interface
Memory organization framed mostly by context and timing, especially the modality and manner of acquisition	Many possible organizational strategies, using catalogues, indexes, titles, tables of content, pagination, etc.
Working memory restricted to a few innate systems, e.g. subvocalizing to oneself, or visual imagination	Working memory is expanded into an external display organized in a rich 3-D spatio-temporal environment
Retrieval from internal memory elicits only weak activation of perceptual brain areas; vivid and precise recall is rare, and often misleading	Exograms can fully activate perceptual brain areas, and can appear to be clearer and more intense than the 'reality' they supposedly represent

many independent fits and starts, these devices became more complex and sophisticated. The built environment was itself an important source of exographic representation, and sophisticated structures, such as the burial mounds at Newgrange, Ireland, often served as primitive computational devices (the mounds in this case were perfectly aligned to measure the occurrence of the winter solstice); forms of artistic expression (such as the very large carved boulders around the base of the mounds), and reminders of social custom (ritual gatherings at the solstice).

The first sophisticated writing systems appeared in Sumer and Egypt, approximately 6000 years ago. Since that time, rapid progress has been made in the refinement of exograms, culminating in modern electronic exographic media. However, that trend was not culturally universal, and the spread of symbolic literacy was usually through diffusion, not parallel invention. Most of the world's languages do not have an indigenous writing system, and many societies of the New Stone Age have had very limited access to sophisticated exographic media of any kind. Nevertheless, the gradual spread of exograms has had a major impact on the collective cognitive resources available to humanity.

Radical properties of exograms

Exographic media have important properties that are absent in natural memory systems, and these have had revolutionary implications for human cognition (Donald 1991; 1993). Those properties include the crucial option of flexible reformatting of the memory record, which affords new opportunities for custom designing more sophisticated cognitive outputs — ideas, records and messages — in which format and content are closely matched. Table 7.2 lists some of those properties.

Exograms typically provide much easier access to conscious examination and visibility of display. Importantly, they also have virtually unlimited storage capacity, and offer organizational niceties such as titles, tables of content, pagination, reference lists, indexes and completely novel search options (such as Googling) that are simply unavailable to the brain's internal memory systems.

The new computer-based technologies also provide a better way to perform certain kinds of cognitive work in distributed hybrid networks that link together many minds with the new technology. Exographic media have introduced the possibility of coordinated intellectual feats (for example, landing a jetliner at Heathrow) that were impossible for human beings in the past. They have permanently changed the ways by which individuals and groups remember, decide and think. And, because they have changed the structure of the larger cognitive-cultural networks that human society can construct, they have allowed the detailed division of cognitive labour.

Neuropsychological sequelae

Sophisticated exogram technology is too recent an innovation for the human brain to have adapted, in the Darwinian sense, to its presence. Nevertheless, most children, from any culture, can acquire full literacy in virtually any system of writing. This argues strongly against a built-in brain adaptation for reading, and in favour of neural plasticity. The 'literacy brain', those circuits that have been identified as the neural foundation of exogram use, is a cultural superimposition upon the brain's innate wiring, and perhaps our best example of the human brain's extraordinary plasticity.

Teaching children to read and write, or training them in the use of any exographic system, including those employed in music and mathematics, changes the internal functional arrangement of certain areas of cortex (Booth *et al.* 2001; 2004; Booth & Burman 2005). The development of literacy-related functional circuits in the brain has been visualized with brain imaging in children by Castro-Caldas *et al.* (1998) and Paulesu *et al.* (2000) and in adults by Eden *et al.* (2004), who found broad organizational changes as a function of increasing expertise. The development of new functional systems for literacy has also been confirmed in adult populations undergoing literacy training (Castro-Caldas *et al.* 1998). In cross-cultural comparisons of adults, a literate brain looks different in its functional organization from an illiterate brain, and this difference continues to increase with age, even in older adults (Brem *et al.* 2006; Petersson *et al.* 2000).

Distinct anatomical circuits of traditional Western literacy skills (alphabetic reading and writing) were known to exist long ago, even in the nineteenth century. They were first inferred from neurological studies of acquired alexias (disorders of reading) and agraphias (disorders of writing), followed by a long tradition of neuropsychological investigation into various subtypes of alexia and dyslexia. Literate adults can manifest very specific deficits in their literacy skills following brain injury. For example, they might experience difficulty in reading irregular words, while remaining able to read those whose orthography is regular (this is known as 'surface' dyslexia, where patients rely heavily on sounding out words). Or they might experience an inability to read non-words (strings of nonsense letters) while remaining able to read concrete, but not abstract, words (this is called 'deep' dyslexia, where patients rely on direct visual access to a word's meaning). These syndromes, and several others, imply the existence in the brain of distinct neural circuits for various aspects of the task of reading.

This kind of deficit has long been attributed to the breakdown of acquired brain networks dedicated to reading and/or writing. While learning to read, the child acquires a new pattern of neural interconnectivity known as a functional 'architecture' within the brain. That architecture does not exist in a preliterate child; it is acquired as a consequence of education. If that neural architecture is damaged in the literate adult, either wholly or in part, literacy skills will break down in a systematic manner, as a function of which part of the architecture has been affected. These disorders often occur independently of aphasias (disorders of spoken language), suggesting that the neural systems devoted to literacy are somewhat independent of those devoted to spoken language.

This fact has had a profound impact on neuropsychological models of language, starting with those of Wernicke (1874), and Lichtheim (1885), and continues to affect modern models, such as Geschwind's (1965), and countless recent theoretical proposals. Although they differ in some details, all of these models specify parallel brain architectures for reading and writing, as well as for other literate skills, such as music and mathematics. Experimental neuropsychological research on this topic, reviewed by Coltheart *et al.* (1980), Shallice (1988), McCarthy & Warrington (1990), Donald (1991), and many others, has further confirmed the existence of several distinctive visual-symbolic architectures in the brain.

The architecture of the literate brain varies slightly between cultures, depending on the kind of writing and numeration systems adopted by those cultures. For example, in native readers, brain lesions affect the ability to read traditional Chinese ideographic characters somewhat differently than the ability to read alphabetic writing (Paradis *et al.* 1985; Li *et al.* 2006). This is partly a reflection of the presence of at least two separate neural paths by which words can be understood, one based on a direct visual access to meaning, and the other based on sounding out the word. Since ideograms do not depend on sound, but rather address meaning directly and visually, they are less vulnerable to injuries that damage the sound pathway; alphabetic reading is different, inasmuch as sound is directly elicited by the form of the word, and the sound pathway is more important.

However, with that relatively minor proviso, many aspects of the standard literacy-related circuitry of the brain appear to be universal (Bolger *et al.* 2005; Chee *et al.* 1999). Recent brain-mapping research using functional MRI has revealed the functional neuro-anatomy of these circuits in much greater detail. Literacy training changes the activation pattern of an area in the occipito-temporal cortex, adjacent to the fusiform region, known as the visual word-form (VWF) region (Cohen *et al.* 2002; Cohen & Dehaene 2004; Gaillard *et al.* 2006). The cells in this region contain the visual codes for each word, and respond to them uniquely, independently of perceptual specifics such as size, location, case, colour or font. Thus, in the trained reader, a specific population of cells will respond to the word 'cat', regardless of how it is represented, whether in upper case, lower case, black, white or coloured print. Printed codes are arbitrary, and can differ radically across different languages. Children must learn the special codes that are appropriate for their cultural and technological environments.

The VWF region is embedded in the so-called 'ventral path' of the cortex, a major visual-perceptual system known to contain a complex interactive hierarchy of cortical regions, each specialized for a particular function, such as extracting contour, colour and form, or computing optical flow patterns. The VWF area is capable of 'mirror generalization', whereby it responds to the mirror image of a written word. This finding suggests that learning to read is not a simple matter of combining new associations in an open associative space, but rather is heavily constrained, proceeding in the same way as we recognize objects, by reconfiguring a cerebral architecture in the VWF area that originally evolved for the purpose of object recognition (Dehaene 2007).

In other words, word forms are treated like objects in the VWF region; they may be unusually abstract and complex cultural objects, but objects nonetheless. This notion is compatible with a wider view of perception as event-perception, in which words are embedded in, and treated like, events, and are closely tied to the event-representational logic of the developing brain (Donald 1991; 2001; Nelson 1986; 2007).

These conclusions apply not only to Western alphabetic literacy, but also to other kinds of written symbols, such as mathematical notations. The decoding of mathematical symbols is mediated by identifiable neural pathways, close to the VWF area, and arranged in a hierarchy of abstraction (Dehaene 2007). One of the clearest results in this field, from a theoretical standpoint, is found in the neuropsychological study of acalculias (various disorders of arithmetical skills), ably summarized by Butterworth (1999). There are at least three cerebral networks involved in basic mathematical skill: an amodal network devoted to intuitive, imprecise estimates of quantity; one that links the latter to specific symbols for number (such as Arabic numerals); and another that runs the actual subroutines for operations, such as subtraction or division. These systems have been visualized with MRI, and they involve mostly the differentiation of regions within the parietal and frontal lobes.

In particular, brain-imaging research on mathematical notations has singled out a structure called the horizontal segment of the intra-parietal sulcus, which is thought to code notation-independent numerical magnitude (Castelli *et al.* 2006; Chochon *et al.* 1999; Dehaene *et al.* 2003; Eger *et al.* 2003; Feigenson *et al.* 2004). Piazza and colleagues have suggested that 'we attach meaning to symbols by physically linking populations of neurons sensitive to symbol shapes to preexisting neural populations holding a nonsymbolic representation of the corresponding preverbal domain' (Piazza *et al.* 2007, 303).

They also point out that our current theories do not yet account for how such symbols acquire exact meanings that go far beyond what is given to pre-symbolic experience. But even though they do not answer this important question, it is clear from these studies that the parietal cortex is a highly plastic structure whose functions can adapt radically, and assume new functions, in the context of intensive education and exographic invention. Further research along these lines should clarify the broader theoretical question about how, with the indispensable aid of notational invention, mathematical thought has advanced so far from our intuitive sense of space, time and quantity.

Musical notations are another important aspect of symbolic literacy. A neuropsychological case study (Capellati *et al.* 2000), the first of its kind, showed a specific sight-reading deficit in a professional musician who had suffered two very localized cortical lesions (due to encephalitis), one in the right occipito-parietal junction, and the other in the posterior part of the left temporal lobe. This patient had completely normal language skills (including reading), and had no disturbance in her other musical skills, such as naming notes, discussing music in abstract verbal terms or playing melodies by heart. This case demonstrates the existence, in an experienced musician, of a distinct cerebral architecture that maps musical notes to performance. Importantly, this architecture was independent of the alphabetic reading system, as well as of other musical skills. The patient could remember and play melodies by heart perfectly accurately; it was only the reading of notes that was completely lost.

Brain-imaging studies (Sergent *et al.* 1992) have shown bilateral activation of extrastriate visual areas when reading music, with concurrent activation of the parieto-temporal junction on the left side. Other studies have suggested different roles for the right and left cortex in musical skill, with symbolic musical functions concentrated mostly on the left side, and non-symbolic functions, such as note perception and melodic memory, on the right. This suggested that a bilateral system may be involved in the reading of musical notations, and this notion has been confirmed in a study of naïve subjects learning to read music. Students were trained to read music for 15 weeks, and brain imaging before and after training showed changes in the activation of bilateral superior parietal cortex and the supramarginal gyrus (Stewart *et al.* 2003; Stewart 2005). These areas are involved in making spatial transformations related to motor learning, and are clearly adapting to the demands of an exographic system that enables music readers to reduplicate patterns of action in a novel technological environment.

There are several convincing examples of great apes learning to use exographic devices to communicate; for example, the bonobo Kanzi can use several hundred visual symbols on a keyboard to express his intentions (Savage-Rumbaugh *et al.* 1998). He has also mastered some simple computer games, as well as the technique of elementary (pre-Oldowan), but useable, stone-tool making. However, there appear to be significant limits on how far such examples can be carried. In his use of symbolic technology, Kanzi resembles a two-and-a-half-year old child; but in other ways, most notably in mimetic communication, such as pantomime and gesture, Kanzi falls far short of human children. To date, no other species has been able to acquire more than a fraction of the skills required to fully master human exographic devices, such as money, totems, books, abacuses, clocks and computers.

Some of this may reflect a relative shortfall in neural plasticity in primates, and suggests that plasticity itself came under selection pressure in human ancestors. The brains of human beings are unusual in their degree of epigenetic plasticity and lifelong capacity for rapid learning. I have suggested the term 'superplasticity' to describe the striking adaptive flexibility of the human neocortex, especially in epigenesis, but also in later life (Donald 2001). Just as the human brain can adapt magnificently to early sensory deprivation, as exemplified in extreme cases, such as those of congenital deafness or blindness, it can also adjust, in the adult, to the demands imposed by new and changing cognitive tools.

In summary, there appear to be two broadly distinct kinds of learning mechanisms involved in the brain's acquisition of symbolic literacy. The first mechanism operates at the perceptual interface, and mediates the relationship between the external symbol and the higher cognitive systems of the brain. This involves the extraction of abstract representations of incoming symbols that enable the brain to process input symbols at high speeds, in the concrete context of a specific sensory modality and a specific task. As Dehaene has suggested (2005), this seems to require the limited modification of highly constrained circuits that evolved mostly for object and event perception. Even at this level, each different class of symbolic notation is processed in an anatomically distinct region of the ventral path, rather than in one all-purpose 'exogram centre'. This might be due to the fact that different exogram domains, such as music, literature and mathematics, need to access quite distinctive cognitive resources at a higher level, and thus acquire different patterns of connectivity. This level of exographic processing does not seem to be entirely unique to the human species, but human children have an extraordinary facility in learning literacy-related skills. In the absence of a specific brain adaptation for literacy, this seems to reflect the plasticity and size of the human cortex.

The second kind of process involved in using exographic devices seems to operate deeper inside the cognitive system, sometimes at a metacognitive (self-reflective) level. It also appears later in development and is slower-moving. It is oriented toward the mastery of task operations, and the refinement of meaning, in various abstract cultural-cognitive domains, such as music, gesture or storytelling. This is where the external symbol really does its cognitive work, interacting with the natural memory systems of the brain. Ideas, feelings and images can be triggered in the reader's brain by written documents, in rapid sequences, and these can be radically rearranged by an author who knows which 'buttons to press', so to speak, in his readers. The cerebral buttons of interest in this case are the so-called lexical entries of any reading system — the words and various other kinds of meaningful symbols that constitute the core of the system. Lexical entries — those essential cerebral networks that encode the semantic, phonological, and grammatical use-rules for every word — are highly complex neural systems that engage many brain regions (Jackendoff 2007). Their existence in a brain enables a writer to trigger predictable responses at a very high level in the reader's mind.

Minds that have acquired full literacy in some domain are made at once more powerful, because they gain access to a shared external resource of ideas and operations; and more vulnerable, because the exographic interface in the brain of a literate person constitutes a direct path into the deepest semantic systems of the brain. The interface architecture, normally acquired in childhood, continues to change throughout adult life. Its acquisition requires considerable resources, and probably involves tradeoffs against the brain's capacities in other areas, but that topic goes beyond the scope of this paper.

The redistribution of cognitive work in society by means of exograms

The availability of specially-trained brains in a given population, combined with a particular variety of exographic media, has enabled human beings to build powerful hybrid human–machine networks that perform some kinds of cognitive work much more effectively than individual minds. This is achieved by 'redistributing' the various elementary subtasks involved in various tasks across many brains and technologies, and by managing and rearranging the allocation of cerebral resources within the wider network.

In modern society, this process of reallocation is mediated largely by designing better interfaces between exographic technology and human beings. Zhang & Norman (1995) have discussed this issue in the context of various mathematical notational systems which redistribute the operations involved in solving a mathematical problem with varying degrees of success. Historically, some notational systems (most notably Arabic numerals) have proven more successful than others, and their relative success seems to be correlated with their ability to reduce and simplify the operations that must be carried out by the mathematician. In other words, the best exographic systems reduce the load on the brain by simplifying some operations, and designing the interface technology so as to focus the mind on task-relevant issues. The juxtaposition of mind and exogram quite literally changes the nature of the task facing the brain. By achieving this kind of redesign, mathematical operations that might have required genius-level skills can be rendered accessible to a multitude of less-talented people.

The emergence of writing systems early in human prehistory marked the beginnings (albeit a slow and uneven start) of a major evolutionary shift in the direction of moving the bulk of memory storage from the brains of individuals to manufactured cognitive artefacts. The size of the external store has grown enormously, and for all intents and purposes, its capacity is unlimited. Modern electronic media are combined with the personal-memory systems of individual brains in very large distributed networks. This has altered the structure of the wider social-cognitive systems that govern cultural evolution, making 'distributed' cognition a dominant presence in the cognitive governance of human society.

The full cognitive impact of this shift has taken several millennia to appear, but as external-memory media have grown larger, more flexible and more easily formatted and reformatted, human society has experienced a cognitive revolution. Human beings now deploy their intellectual resources, both inside and outside the brain, in new ways. Decisions are made, perceptions are changed, programs of action are planned and events are remembered, in millions of brains, through the mediation of external devices of all kinds. The central nervous system is still the creative driver of the exographic system, but the latter has vastly exceeded the memory storage and retrieval capacity of any brain.

One of the most dramatic advantages conveyed by exograms is the flexibility and speed of adaptive change in the shared-memory resources of society. This is largely due to changes introduced by the invention of increasingly better exographic technology. The memory systems of the human brain are limited to a few relatively inflexible biochemical and anatomical media. Retrieval from these media has proven inaccurate and unreliable; in order to recall biological memories, the mind must rely on the three ancient methods available to the brain: association in time and space and similarity. These mechanisms of retrieval are clumsy, inaccurate and slow. Biological memories themselves are also impermanent, extremely difficult to display, review and edit, and subject to unpredictable distortions and changes. When brought into consciousness, the display and review of such memories depend upon another natural subsystem of the brain, short-term memory, which is itself even more limited and unreliable.

In societies that maintain a true oral tradition, uncontaminated by exposure to modern literate cultures, there are few, if any, exographic media available for recording the accumulated collective knowledge of the group; and those media that are available are very limited. The collective memory of such societies must be confined largely to the brains of its members. Memories are transmitted and held in highly stylized and repeatedly rehearsed stories, along with shared ritual mimetic practices. Major items, such as knowledge of medicinal herbs and poisons, or important myths, are typically memorized by trained specialists, such as bards or shamans. Such systems are rigid and difficult to change. Training in mnemonics and oratory, one of the primary aims of education in the political oral culture of ancient Greece, and still practised into the twentieth century in the West, conveyed only a slight advantage to those who underwent such training. Without exographic storage, much of the cognitive energy of the group was tied up simply in maintaining traditions and structures.

The hard truth is that natural or biological memory records are very limited. A complete dependency on biological memory greatly constrains the rate of technological and social change in oral cultures. These limits are inevitable as long as such societies do not have powerful exographic technologies, such as written records, because the storage and retrieval properties of innate memory systems apply not only to individuals, but also to the larger shared social-cognitive system of the group. Even such elementary practices as trade and taxation require a writing system to record and track the multitude of transactions necessary for them. Moreover, the absence of written records impairs a society's capacity to reflect on, and refine, its mental representations. In effect, its cognitive options are greatly foreshortened, when compared to those of a highly literate culture.

Exograms created powerful new possibilities, and greatly increased the powers of the collective cognitive system. As the technology of representation has become more powerful, so has society. This can occur rapidly, without requiring any Darwinian adaptations of the brain, or increases in individual intelligence. Rather, it requires the reallocation of available neural resources in the population, along with a different division of cognitive labour, and extensive epigenetic reprogramming of the brain.

Societies equipped with new memory media, and sufficiently experienced in the uses of literacy, have changed and adapted more rapidly to the cognitive demands of modern social change, such as the shift to centralized agriculture, or to urban living. This adaptive flexibility has entailed several factors, including reshuffling the cognitive roles played by individual minds, and further division of cognitive labour. Improvements in exographic technology itself were central to this evolution, and, at the same time, led to the development of increasingly complex institutional structures (for instance, banks and government bureaucracies) that are completely dependent on exographic technology for their existence.

It is, of course, a truism that the cultural buck stops ultimately at the threshold of personal consciousness. People must be able to acquire the appropriate skills to use their exographic technologies effectively, and to interact with them. Learning these skills consumes most of the early years of development, and an exographic device that exceeds the capacity of its users will not succeed. Designers of new symbolic technologies must take this fact into account in order for the technology to be effective. Entire new industries of interface design are the result of this. Exographic technology continues to change profoundly the cognitive games people play.

Only three hundred years ago, Erasmus wrote that he had travelled for several days through the Low Countries without his books or notes, and consequently, had gone the entire time without seeing a single written word; not so much as a written signpost was visible. Today, most of the developed world has the opposite problem; its symbol-addicted citizens can never seem to escape the unceasing barrage of logos, signs, magazines, newspapers, TV images, email and other messages that electronic devices, such as 'smart' cell phones and Blackberries, communicate 24 hours a day. The memories stored outside the brain vastly outnumber those stored within. The stream of individual consciousness, down to a level of great detail, is subjected to exquisitely crafted and highly concentrated external programming, as in, for example, advertising or movies.

The greater part of our memory records are now stored in exograms, rather than engrams. Much of the work of modern society centres on the maintenance of external memories, and on the operation of the external symbolic storage system that human beings have built. Workers in libraries, archives, the international financial system, the courts, science, education and literature are all largely employed in the creation, servicing and editing of exograms. Moreover, experience itself is increasingly shaped and framed by exographic media. While it is still the human observer who makes decisions and judgments with regard to thought and action, it seems that the exographic revolution — the exporting of the human memory record from brains to exographic media — is almost complete.

When viewed against the longer time course of human prehistory, exographic representations in general, and systems of writing in particular, are relatively recent inventions. The oldest writing systems are not more than 6000 years old, and their predecessors, in such things as trading tokens, are probably not more than 10,000 years old. Given that modern humanity emerged as a distinct species approximately 160,000 years ago, this means that writing has existed for less than 10 per cent of our tenure on Earth.

Seen in this very wide temporal frame, the recent technological explosion brought about by the invention of printing and electronic media is the end product of a long process of social and technological change. It has undoubtedly accelerated the long-standing symbiosis of the brain with the external symbolic world it has created, and put pressure on the young to assimilate more and more complex technologies. There is no longer any doubt that this symbiosis of brain with communications technology has a massive impact on cortical epigenesis and, with the rise of mass literacy, that this effect is present in a very large percentage of the human population.

The driver of that increasingly rapid rate of change, human culture, can be regarded as a gigantic search engine that seeks out and selects the kinds of brains and minds it needs at a given historical moment. The technological and symbolic innovations of the last few centuries have forced cultures to value certain kinds of nervous systems because they fit the current high-tech agenda. Modern culture hunts for, and picks for training, those brains that lend themselves best to the particular sort of cognitive rewiring imposed by the new technology, and this in turn drives the emergence of new kinds of literate elites.

This process has introduced a somewhat unpredictable selection factor into cultural and cognitive evolution, whereby the talents to be 'rewarded' by recruitment into the elite in one generation may not be the same as the ones needed in the next. With the gradual invention of more accessible exographic technologies, the spread of mass literacy has deeply affected the selective mass programming and reprogramming of millions of brains. Judging from the brain-imaging studies at hand, our ancient brain anatomy is being redeployed for new ends, in new functional architectures. The principle of neural re-entrance (Edelman 1987) is undoubtedly at work here, enabling the top-down conversion of lower-level brain circuitry to meet the cognitive demands of literate society.

The joining of those reprogrammed brains into a worldwide network has been mediated by several generations of training and adaptation, and the result remains as unpredictable as in the past. As high technology continues to change, it is safe to assume that social priorities will also change, and this will affect the kinds of talents needed to sustain the network. What kinds of literacy skills, and hence what kinds of brains, will be valued in the next generation? No one can predict. The outcome will depend heavily on both the limits of technological design and political values.

Whether viewed in terms of the functional architecture of the brain, or the larger cognitive capacities of the human species, this trend toward externalizing memory and restructuring the larger social-cognitive system has generated a radical change in the intellectual powers collectively at the disposal of humankind. Human society is now governed by a distributed, technologically aided cognitive system that is evolving at a rapid pace. The brains of modern 'knowledge workers' are wired into organizations and networks that cannot possibly function without the plethora of external symbolic technologies that drive the modern scientific and governmental effort. At the same time, the networks cannot function without continuous educational reprogramming of the brains of the workers embedded in them. The same principle applies to finance, medicine and education, all of which are heavily wired into exographic technology; and it applies even to such artistic endeavours as symphonic music, theatre and film. There are corresponding changes being considered in our educational institutions, but it is questionable whether they are keeping up with the rate of change.

References

Bolger, D.J., C.A. Perfetti & W. Schneider, 2005. Cross-cultural effect on the brain revisited: universal structures plus writing system variation. *Human Brain Mapping* 25, 92–104.

Booth, J.R. & D.D. Burman, 2005. Using neuroimaging to test developmental models of reading acquisition, in *The Connections between Language and Reading Disabilities*, eds. H. Catts & A. Kamhi. New York (NY): Lawrence Erlbaum Associated, 114–34.

Booth, J.R., D.D. Burman, F.W. Van Santen, *et al.*, 2001. The development of specialized brain systems for reading and oral-language. *Child Neuropsychology* 7, 119–41.

Booth, J.R., D.D. Burman, J.R. Meyer, *et al.*, 2004. Development of brain mechanisms for processing orthographic and phonological representations. *Journal of Cognitive Neuroscience* 16, 1234–49.

Brem, S., K. Bucher, P. Halder, *et al.*, 2006. Evidence for developmental changes in the visual word processing network beyond adolescence. *NeuroImage* 29, 822–37.

Butterworth, B., 1999. *The Mathematical Brain*. London: MacMillan.

Capellati, M., H. Waley-Cohen, B. Butterworth & M. Kopelman, 2000. A selective loss of the ability to read and to write music. *Neurocase* 6, 321–31.

Castelli, F., D.E. Glaser & B. Butterworth, 2006. Discrete and analogue quantity processing in the parietal lobe: a functional MRI study. *Proceedings of the National Academy of Sciences of the USA* 103, 4693–8.

Castro-Caldas, A., K.M. Petersson, A. Reis, S. Stone-Elander & M. Ingvar, 1998. The illiterate brain. *Brain* 121(6), 1053–63.

Chee, M.W.L., D. Caplan, C.S. Soon, *et al.*, 1999. Processing of visually presented sentences in Mandarin and English studied with fMRI. *Neuron* 23, 127–37.

Chochon, F., L. Cohen, P.F. van de Moortele & S. Dehaene, 1999. Differential contributions of the left and right inferior parietal lobules to number processing. *Journal of Cognitive Neuroscience* 11, 617–30.

Cohen, L. & S. Dehaene, 2004. Specialization within the ventral stream: the visual word-form area. *NeuroImage* 22, 466–76.

Cohen, L., F. Lehericy, C. Chochon, S. Lemer, S. Rivaud & S. Dehaene, 2002. Language-specific tuning of visual cortex: functional properties of the visual word-form area. *Brain* 125, 1054–69.

Coltheart, M., K. Patterson & J.C. Marshall (eds.), 1980. *Deep Dyslexia*. London: Routledge.

Dehaene, S., 2005. Evolution of human cortical circuits for reading and arithmetic: the 'neuronal recycling' hypothesis, in *From Monkey Brain to Human Brain*, eds. S. Dehaene, M. Hauser & G. Rizzolatti. Cambridge (MA): MIT Press, 133–57.

Dehaene, S., 2007. Cultural recycling of cortical maps. *Neuron* 56, 384–98.

Dehaene, S., M. Piazza, P. Pinel & L. Cohen, 2003. Three parietal circuits for number processing. *Cognitive Neuropsychology* 20, 487–506.

Donald, M., 1991. *Origins of the Modern Mind: Three Stages in the Evolution of Culture and Cognition*. Cambridge (MA): Harvard University Press.

Donald, M.W., 1993. Précis of *Origins of the Modern Mind* with multiple reviews and author's response. *Behavioral and Brain Sciences* 16, 737–91.

Donald, M.W., 1998. Hominid enculturation and cognitive evolution, in *Cognition and Material Culture: the Archaeology of Symbolic Storage*, eds. C. Renfrew & C. Scarre. (McDonald Institute Monographs.) Cambridge: The McDonald Institute for Archaeological Research, 7–17.

Donald, M., 2001. *A Mind So Rare: the Evolution of Human Consciousness*. New York (NY): W.W. Norton.

Edelman, G., 1987. *Neural Darwinism: the Theory of Neuronal Group Selection*. New York (NY): Basic Books.

Eden, G.F., K.M. Jones, K. Cappell, *et al.*, 2004. Neural changes following remediation in adult developmental dyslexia. *Neuron* 44, 411–22.

Eger, E., P. Stertzer, M.O. Russ, A.L. Giraud & A. Kleinschmidt, 2003. A supramodal number representation in human intraparietal cortex. *Neuron* 37, 719–25.

Feigenson, L., S. Dehaene & E. Spelke, 2004. Core systems of number. *Trends in Cognitive Sciences* 8, 307–14.

Gaillard, R., L. Naccache, P. Pinel, *et al.*, 2006. Direct intracranial, fMRI, and lesion evidence for the causal role of left inferotemporal cortex in reading. *Neuron* 50, 191–204.

Geschwind, N., 1965. Disconnection syndromes in animals and man. *Brain* 88, 237–324, 585–644.

Jackendoff, R., 2007. *Language, Consciousness, Culture: Essays on Mental Structure*. Cambridge (MA): MIT Press.

Lashley, K.S., 1950. In search of the engram, in *The Neuropsychology of Lashley*, eds. F. Beach, D.O. Hebb, C. Morgan, & H. Nissen. New York (NY): McGraw Hill, 338–44.

Li, G., R.T.F. Cheung, J.H. Gao, *et al.*, 2006. Cognitive processing in Chinese literate and illiterate subjects: an fMRI study. *Human Brain Mapping* 27, 144–52.

Lichtheim, L., 1885. On aphasia. *Brain* 7, 433–84.

McCarthy, R. & E. Warrington, 1990. *Cognitive Neuropsychology*. San Diego (CA): Academic Press.

Nelson, K., 1986. *Event Knowledge: Structure and Function in Development*. Hillsdale (NJ): Lawrence Erlbaum Associates.

Nelson, K., 2007. *Young Minds in Social Worlds: Experience, Meaning, and Memory*. Cambridge (MA): Harvard University Press.

Paradis, M., H. Hagiwara & N. Hildebrandt, 1985. *Neurolinguistic Aspects of the Japanese Writing System*. Orlando (FL): Academic Press.

Paulesu, E., E. McCrory, F. Fazio, *et al.*, 2000. A cultural effect on brain function. *Nature Neuroscience* 2, 91–6.

Petersson, K.M., A. Reis, S. Askelof, A. Castro-Caldas & M. Ingvar, 2000. Language processing modulated by literacy: a network analysis of verbal repetition in literate and illiterate subjects. *Journal of Cognitive Neuroscience* 12, 364–82.

Piazza, M., P. Pinel, D. LeBihan & S. Dehaene, 2007. A magnitude code common to numerosities and number symbols in human intraparietal cortex. *Neuron* 53, 293–305.

Savage-Rumbaugh, E.S., S.G. Shanker & T.J. Taylor, 1998. *Apes, Language, and the Human Mind*. New York (NY): Oxford University Press.

Sergent, J., E. Zuck, S. Terriah & B. MacDonald, 1992. Distributed neural network underlying musical sight-reading and keyboard performance. *Science* 257, 106–9.

Shallice, T., 1988. *From Neuropsychology to Mental Structure*. New York (NY): Cambridge University Press.

Stewart, L., 2005. Neurocognitive studies of musical literacy acquisition. *Musicae Scientiae* 9, 223–37.

Stewart, L., R. Henson, K. Kempe, V. Walsh, R. Turner & U. Frith, 2003. Brain changes after learning to read and play music. *NeuroImage* 20, 71–83.

Tulving, E., 1985. How many memory systems are there? *American Psychologist* 40, 385–98.

Wernicke, C., 1874. *Der Aphhasische Symptomkomplex*. Breslau: Cohn & Weigart. [Trans. and republished in *Boston Studies in Philosophy of Science* 4, 34–97.]

Zhang, J. & D. Norman, 1995. A representational analysis of numeration systems. *Cognition* 57, 271–95.