Congenital word-blindness – making sense of wiring diagrams and 'black boxes': discussion paper

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Reading and writing represent the apogee of coded means of communication in the animal world. They are unique to humans. Although the written word lacks much of the versatility of the spoken word, and the gestures that accompany it, it does free human communication from the evanescent character of verbal language.

The history of written language is young, however – spanning some 5000 years from the development of cuneiform script by the Sumerians. The earliest 'man' (*Australopithecus*), on the other hand, probably appeared some 3–5 million years ago; it has been argued by some anthropologists that spoken language must have existed at that time[1].

A distinction between the acquisition of the written and spoken word is also apparent in ontogeny; a child naturally develops speech before it has been taught to read. Thus the human experiment in reading is relatively young and may depend upon competence in speech. In this context it may not be surprising to learn that 5–10% of children have difficulties in reading Western script. The decoding of visual symbols which are not merely representations of physical forms but which carry phonetic as well as abstract content makes formidable demands on any information-processing system. Witness the notable inadequacies of artificial intelligence experts to program computers which can read as humans do.

Levels of explanation

Developmental dyslexia, or congenital word-blindness as it was called by Morgan[2], is defined by exclusion. The World Federation of Neurology considers it to be a 'disorder manifested by difficulty in learning to read despite conventional instruction, adequate intelligence and sociocultural opportunity'[3]. Apart from begging a number of questions (e.g. What is adequate intelligence?), such a definition suggests that it is not possible to diagnose dyslexia in children from 'deprived' backgrounds, further fuelling suspicions that dyslexia is indeed only a 'middle-class disease'.

Theories which have sought to establish a neural explanation of the condition have been numerous and conflicting – neurological[4] and psychological[5]. In this discussion I unashamedly lay emphasis on certain recent speculations which have yet to be confirmed. These ideas are derived from experiments conducted on normal humans and monkeys, as well as from humans suffering from the experiments of nature.

One might imagine that a major hindrance to understanding the causes of developmental dyslexia is the lack of firmly established site(s) of lesion. Unfortunately 'lesion-spotting' *per se* can be a misguided exercise. Consider the acquired dyslexias; those resulting, for example, from stroke in adults. The celebrated French neurologist Jules Dejerine, in 1892, had proposed sites of pathology which have since been amply confirmed[6,7]. Yet his ideas of the disconnection of cortical centres illuminate only in a very general way the functions of centres so separated.

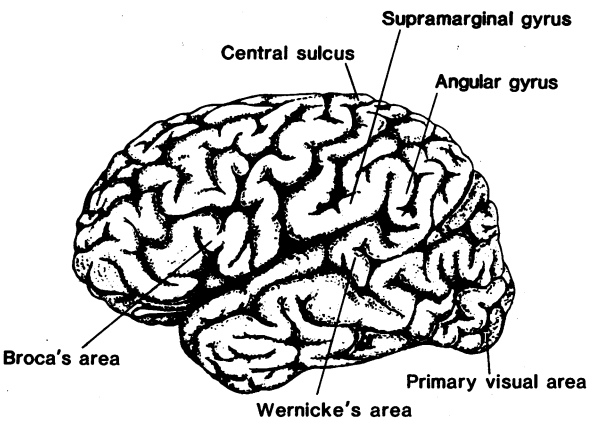

Figure 1. Lateral aspect of the left cerebral hemisphere of humans. 'Linguistic functions' have traditionally been thought to be lateralized to the left hemisphere, whereas the right is supposed to be specialized for visuospatial functions. Whether this is the fundamental distinction between the modes of operation of the two hemispheres is a matter of lively current debate. The functions of Broca's area (sound-production organization) and Wernicke's area (sound analysis) are 'revealed' by their loss in aphasic patients. The angular gyrus and the supramarginal gyrus constitute Brodman's areas 39 and 40 to a rough approximation. The homologous area (a part of the inferior parietal lobule) in other species such as monkey is relatively rudimentary. This area is one of the last to myelinate in the human brain. It has been suggested that retarded development of the angular gyri may lead to developmental dyslexia[6]

In essence, Dejerine contended that the angular gyrus of the left cerebral hemisphere contained a centre for the 'optical image of letters' (Figure 1), without which a subject would suffer from problems in writing as well as reading (alexia-with-agraphia). Pure alexia (i.e. without agraphia) would result if only the afferent visual pathways from both left and right visual cortices were compromised – effectively disconnecting the left angular gyrus from its visual input, but having no effect upon its capacity to evoke the images of letters required in writing (Figure 2B).

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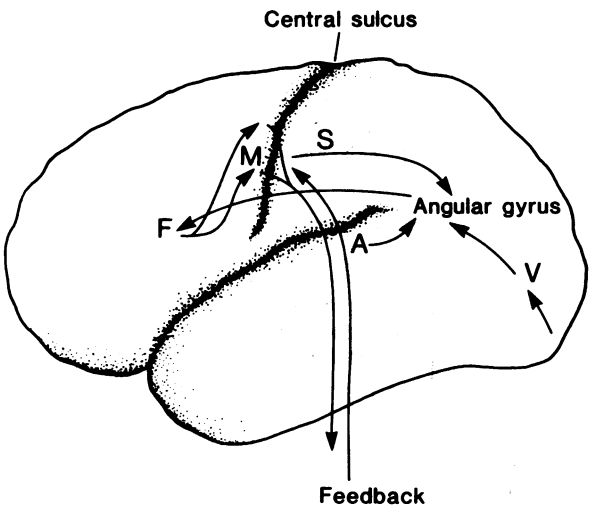

Figure 2A. The angular gyrus as an 'association area of association areas'. Geschwind[6] drew attention to the fact that information from visual (V), auditory (A), and somaesthetic (S) association areas converge upon the angular gyrus. This region of the brain has, at least, the capacity to associate sounds with symbolic material presented through either visual or somaesthetic modalities. Reading is thought to depend upon such associations. Writing may require the engagement of centres in the frontal lobe (F) which, in turn, activate the relevant zones of the motor cortical strip (M). Feedback information from muscles and joints participating in writing passes from the somatosensory cortex to the angular gyrus

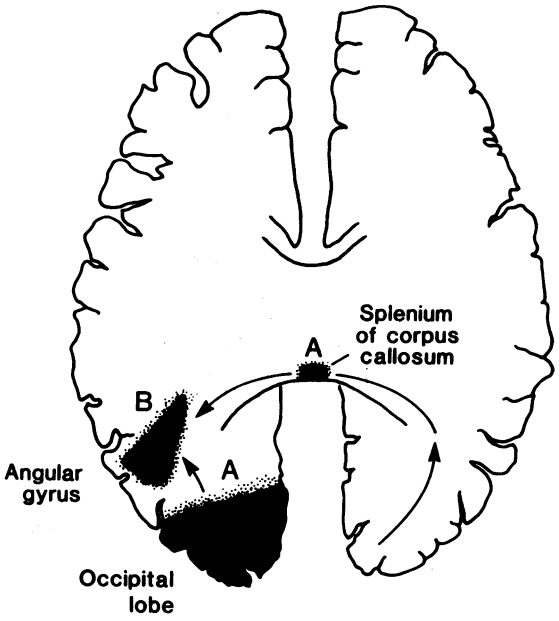

Figure 2B. Lesions producing pure alexia (A) or alexia-with-agraphia (B). Disconnection of the angular gyrus from both visual cortices results in pure alexia since associations between visually presented script and the sounds of words can no longer be made (A). A lesion of the angular gyrus alone also produces problems in writing because the capacity to evoke 'images' of letters is compromised (B)

What does this tell us of how the brain deals with written script or language? Very little, directly. Although disconnections may occur, what, for example, does this reveal of the neural mechanisms which allow the angular gyrus to act as a visual memory centre for words? At one level of explanation, that of anatomy, Norman Geschwind's proposal[6] that the angular gyrus, by virtue of its location, acts as a region for forming and storing associations between various sensory modalities (Figure 2A) was more instructive.

The notion that linguistic competence depends upon associations between, say, vision and hearing (in order to match written word to corresponding spoken sound) implies that the mechanism employed in reading may not be unique to the reading process. This is not a new idea; nor did Geschwind intend it to be an exclusive explanation of the reading process. He stressed that such associations may be important in the development of reading. It is clear, as Hinshelwood[8], one of the pioneers in the study of word-blindness, noted in 1900, that the normal reader reaches a stage when 'the words ... cease to be ... simply a congeries of letters; each word is regarded as an ideogram, picture, or symbol ... The individual now recognises a word, just as he recognises a landscape or a familiar face, by its general outline and form'.

Thus the normal reader has direct (visual) access to meaning (reading by eye) as well as a phonic route (reading by ear) suggested by Geschwind, whereby a word is sounded out by associating a letter with a particular sound[9]. One could envisage that the latter route may employ anatomical substrates in the left hemisphere, such as Wernicke's area, which seems to be essential for speech comprehension.

The neuropsychological testing of alexics has further revealed that there are many subtle forms of acquired dyslexia which are (*a*) delineated by the type of reading errors made; and (*b*) not readily associated with discrete cortical lesion sites[9-12]. For example, (acquired) phonological dyslexics, although they have lost the ability to associate letter with corresponding sound, can nevertheless understand familiar words. It would appear from such psychological studies that reading depends upon a system of subcomponents or modules consisting of cognitive 'processors'. This is another level of explanation, that of the 'black box' (Figure 3).

Both levels of explanation, that of pure anatomy and that of the 'black box', offer little hope for the formulation of testable hypotheses which correlate structure with function in a meangingful way. Both, in my opinion, are inadequate. How does this discussion on acquired dyslexia relate to the developmental condition? In simple terms, some researchers have attempted to demonstrate analogies between anatomical and cognitive observations made in acquired dyslexia and some results obtained from a few developmental dyslexics[13-15]. As I have made plain, I consider such explanations, in themselves, to be of limited value.

Physiological approaches

An alternative level of explanation, a physiological one, has been considered improbable. First, until recently there was no effective means of studying the functional activity of the human brain whilst a subject performs relevant tasks. With the advent of regional blood flow studies[16], new means of topographically displaying EEG and evoked potential data[17], and new imaging methods such as positron

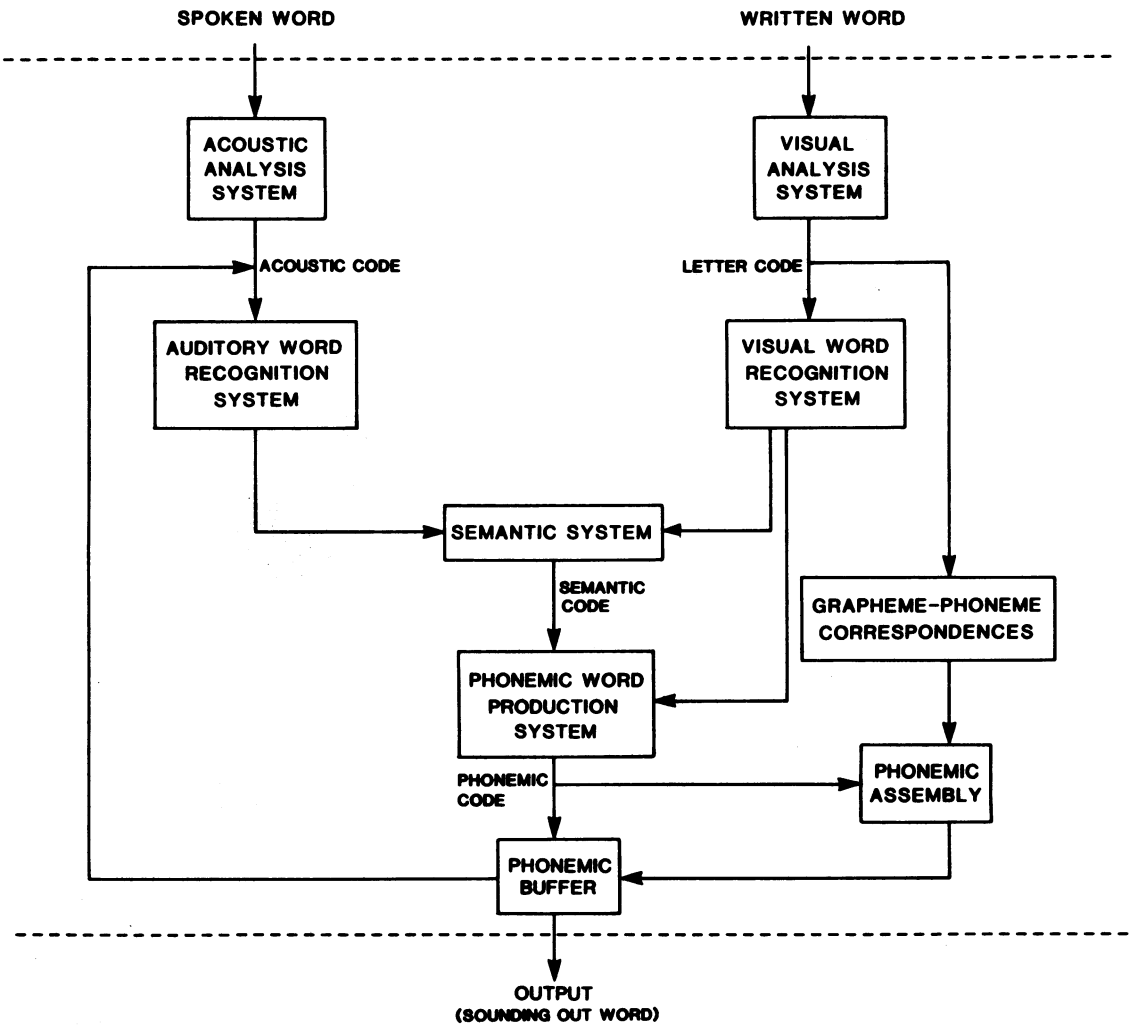

Figure 3. Model for both direct and phonically mediated recognition, comprehension, and naming of written words (adapted from Ellis[9]). It is not essential to understand the details of the scheme in the context of this discussion. The model is included to illustrate the cognitive 'black box' level of explanation. Reading is thought to result from the concerted activity of various cognitive subcomponents or modules. Problems in reading occur if certain critical modules are not functioning in the correct manner, or if modules become functionally isolated (cf. disconnection syndromes). In phonological dyslexia, for example, patients lose the ability to read simple nonsense words such as 'NIM' although they are capable of understanding familiar real words. This implies that there must be a route directly from print to meaning (i.e. access to the semantic system) which is independent of the route via letter-sound conversion (grapheme-phoneme correspondences). It has been suggested that the second route is of great importance in the development of reading skills, and when a competent reader comes upon a visually unfamiliar word. With familiar words, most readers are thought to read by eye, i.e. via the direct route

emission tomography (PET)[18] and ^{31}P nuclear magnetic resonance (NMR)[19], it may be possible to approach the discovery of neural correlates of cognitive processes.

Second, despite the availability of these imaging techniques, it is apparent, for ethical reasons, that some form of animal model may be required in order to manipulate the organization of the brain and thereby test hypotheses actively. For many readers the pre-eminence of human communicative skills in the animal world may make it difficult to understand the relevance of experiments conducted in monkeys. Without indulging in a discussion on the linguistic abilities of other primates, I would submit that it is not unreasonable to assume that many of our cognitive processes make use of, or have elaborated upon, neural mechanisms which are also present in monkeys and apes (see below).

Eye movements and developmental dyslexia

Consider the visual control of movement. The reactions of both monkeys and humans to events in the world around us depend, amongst other things, upon accurate localization of objects. Our eyes view the world from a mobile platform, the head, and are themselves capable of moving independently with respect to the head. Thus the location of a visible object cannot be simply determined from the positions of its images on the retinae.

In order to establish the absolute direction of an object in 'extrapersonal space', one needs to transform retinotopic space into 'real' space. It has been argued that this is effected by means of another type of association, that of extraretinal signals of eye position (i.e. proprioceptive signals from the orbit or corollory discharges from motor centres) with retinal signals[20]. If the reader has difficulty with this concept, it may be helpful to imagine inspecting a set of photographs taken from the centre of an unfamiliar room. Without tagging each photograph with the direction in which the camera was pointing it would be difficult to build up an accurate awareness of the spatial relations of objects which are not in the same or overlapping

snapshot. Similarly, the brain needs to tag each retinal 'snap' with the information about the direction in which the eye is pointing.

Stein and Fowler[21] have recently presented evidence which suggests that some developmental dyslexics are unable to associate reliably these two sets of signals. Consequently, they do not know exactly where their eyes are pointing. This may account for the complaints of some dyslexics that letters appear to reverse themselves, move about, and run into each other. It may also explain why some dyslexics are dysgraphics.

Stein and Fowler[22] found that simply patching one eye during reading resulted in significantly faster reading progress compared with unoccluded 'visual dyslexics'. This was attributed to the relief from confusing retinal and extraretinal position signals provided by the two eyes.

Geschwind[6], for the purposes of his own theory, drew attention to the relatively rudimentary form of the angular gyrus in primates other than man. But what do we know of the inferior parietal lobule in monkeys? Mountcastle and his associates have demonstrated neurones in this region which discharge prior to visually directed movements of the eye or hand[23]. Cooling the same area in monkeys leads to mislocations of objects in the contralateral hemifield[24], a symptom reminiscent of that seen after posterior right hemisphere lesions in humans[25]. The fact that paralysis of gaze is also more common in such cases[26] suggests that the right hemisphere may be specialized for active, as well as 'passive', visuospatial functions.

Reading by eye may now be partly understood in terms of the efficient sequencing of reliable associations of retinal and extraretinal information. Indeed, reading may epitomize what one might term 'active sight' – the process whereby specific eye movement patterns have developed to scan symbolic material rapidly, and simultaneously to extract an enormous amount of detail. In the context of the evolution of reading skills, it is pertinent to note that only primates possess eye movements which are disjunctive, i.e. allow the eyes to converge and diverge[27]. When we read, we not only make saccades across a line of print but we also alter the angle of convergence between the two eyes. These vergence movements may be particularly vulnerable to disruption; Stein, Riddell and Fowler (in preparation) have recently demonstrated that visual dyslexics are unable to track accurately the movements of small targets in a vergence task. It may not be a coincidence that neurones responsive during such movements have been identified in the inferior parietal lobule of monkeys[28]. As we have seen, the angular gyrus is the site of convergence of sensory information; there is no reason to suppose that the associations between retinal and extraretinal position signals which occur in this region in monkeys do not also occur in humans.

There is some circumstantial evidence in favour of these speculations:

(1) Reading disorders may be associated with oculomotor disorders[29].
(2) Gordon Holmes[30], the eminent British neurologist, described a patient suffering from acquired pure word-blindness who, in describing his symptoms, observed: 'I feel I can read the letters, but when I try they seem to get mixed up and blurred' and 'I don't know what letter I am trying to see'.
(3) Some dyslexic children may exhibit erratic eye movements during reading[31] as well as during sequential tracking of lights[32], suggesting that in some children faulty oculomotor control is a primary cause.
(4) Reading difficulties can arise from right parietal lobe lesions[33], and have previously been attributed to a defective synthesis of retinal information with proprioceptive information from ocular muscles[34].

Hemispheric specialization

How do the above observations, which emphasize the visuospatial (and, by implication, right hemisphere) skills in reading, relate to the lateralization of linguistic functions in the left hemisphere in normals (Figure 1)? One must entertain, as many have done previously, the possibility that in developmental dyslexics hemispheric specialization is effectively disordered[35,36], and that this may be at the root of the condition. Topographical mapping of evoked potential data certainly reveals greater differences between normal male readers and dyslexic boys in the posterolateral regions of both the left and the right hemisphere depending on the nature of the task[37]. One may speculate that whereas reading by ear requires left hemisphere processing, reading by eye involves the recruitment of right hemisphere mechanisms.

The defective eye-position sense hypothesis is controversial, however. As it stands, it is not much better than a 'black box' level of explanation. But its instructive value lies in its potential: (*a*) it can be tested rigorously in dyslexics and in monkey models (extraretinal and retinal associations can be impaired by surgical intervention); and (*b*) with the introduction of new imaging techniques it lends itself to tests in which records of eye movements may be related to cortical activation parameters (e.g. magnitude or location) in the human brain. While it is an intriguing possibility that hemispheric differences in angular gyrus activity might be implicated in such studies, there is yet more physiological evidence upon which we can draw.

The cortical mantle, at least in the primary sensory and motor areas and also possibly in the association areas, is composed of vertically aligned functional columns which Mountcastle[38] suggests are 'the basic unit(s) of operation in the neocortex'. The enlargement of the human frontal and parietal association areas may be envisaged, as hinted at earlier, as having occurred by the replication of these modules rather than by the evolution of different neural networks.

Each column performs a 'primary repertoire', and variation in columnar output is thought to be a function of the connections of the column rather than a function of its intrinsic structure. Thus, in a thought-experiment at least, one could imagine that swopping cortical columns from different regions of the cortex would not have any effect upon cortical function, provided that afferent and efferent connections characteristic of a columnar position were retained (Figure 4).

If this were proved to be the case across the hemispheres, it would imply that the origins of lateralization of cognitive functions ('black box' level) may be found in the hard-wiring (anatomical level). I

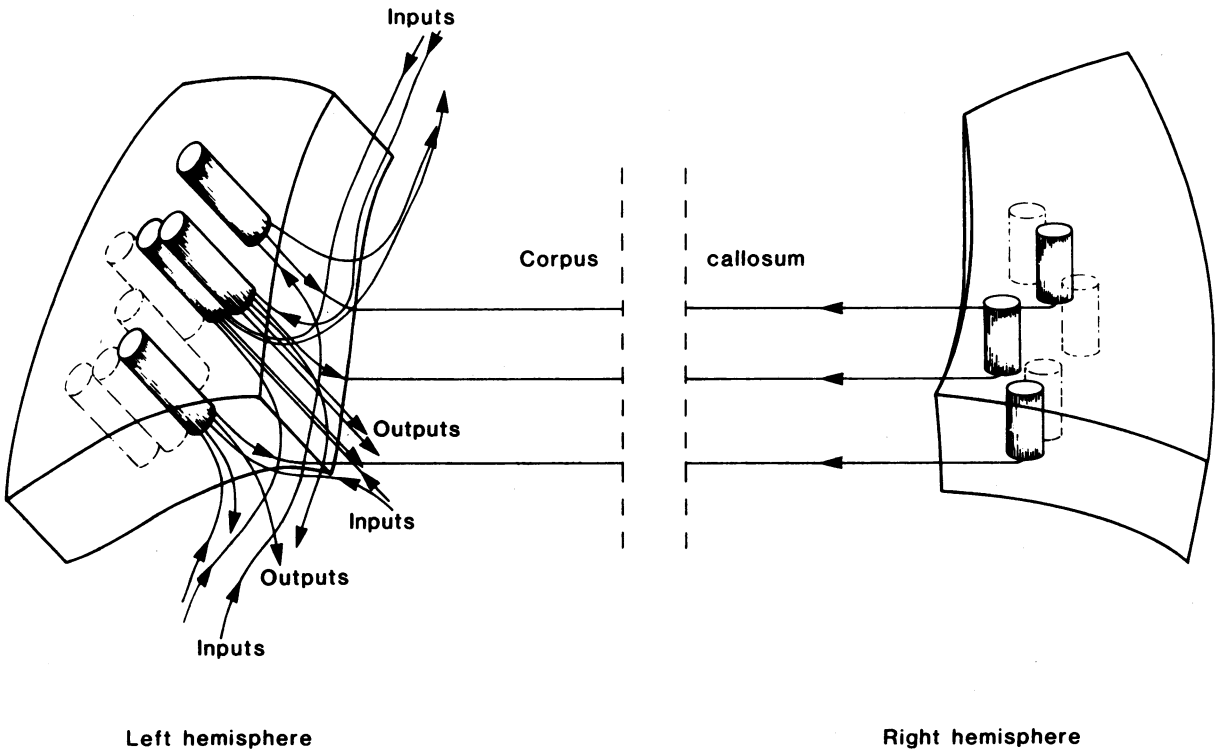

Figure 4. The column as the unit input–output module of the neocortex. The vertical alignment of groups of cells with functionally similar characteristics appears to be an important organizational principle in the cortex. It has been suggested[38] that each column has a similar 'primary repertoire' and that the differences in columnar activity are a function of columnar connectivity. The figure illustrates, in a highly schematic manner, a number of activated columns within the left hemisphere together with their inputs and outputs. Columns in the right hemisphere which send inputs, via the corpus callosum, to the activated left hemisphere columns are also depicted. The known functional differences between the left and right hemispheres may be ascribed to: (a) different sets of connections for homologous columns in each hemisphere, or (b) different sets of 'primary repertoires' performed by homologous columns. If it is the latter then there may be subtle neurochemical diferences rather than variation in intrinsic columnar connectivity

suspect that it is not the fibre connections which differ between the hemispheres but rather the primary repertoires (operations) performed by the columns in homologous areas. Such differences may not be deducible from classical anatomical wiring diagram studies. They may be more subtle. For example, it has recently been shown that there is a lateralization of choline acetyltransferase in the first temporal gyrus of humans which changes between the fetal and adult states[39]. It is nevertheless evident that in trying to unravel brain function at this level one should make use of anatomical methods, such as immunocytochemical staining, as well as 'black box expertise'. Together these techniques may help to elucidate the computational functions performed by a column. The aim of such studies would be to correlate these results with meaningful, and quantifiable, behavioural activity.

If Mountcastle's theory proves to be correct, it is a (distant) possibility that the activity of a column, or group of columns, in humans involved in, say, some aspect of eye movement control could be inferred by combining results from microelectrode studies in monkey with a knowledge of the wiring and the primary repertoire of the column. Of course, one could not imagine such analysis to be simple; cortical function depends upon the activity of many groups of columns. But even if their connectivities and computations were known, it is my belief that only by resort to 'listening-in' to the electrical transactions of columns can we hope to understand the emergent behaviour of each.

A major theme in this paper has been the 'adequate level of explanation'. Obviously this level is a rather subjective one; some may feel that their adequate level is at that of the gene. I have merely directed the reader's attention to the potential for physiological approaches to 'higher functions' of the nervous system and their disruption by disease or inappropriate development. The Stein and Fowler model of developmental dyslexia is certainly not an exclusive one. Nor does it account for 'non-visual' reading problems[40]. But it offers a challenging opportunity to make sense of wiring diagrams and 'black boxes'.

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