

A Unitary Hypothesis of Mind--Brain Interaction in the Cerebral Cortex

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A unitary hypothesis of mind–brain interaction in the cerebral cortex

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[Plates 1–6]

A brief introduction to the brain–mind problem leads on to a survey of the neuronal structure of the cerebral cortex. It is proposed that the basic receptive units are the bundles or clusters of apical dendrites of the pyramidal cells of laminae V and III–II as described by Fleischhauer and Peters and their associates. There are up to 100 apical dendrites in these receptive units, named dendrons. Each dendron would have an input of up to 100 000 spine synapses. There are about 40 million dendrons in the human cerebral cortex.

A study of the influence of mental events on the brain leads to the hypothesis that all mental events, the whole of the World 2 of Popper, are composed of mental units, each carrying its own characteristic mental experience. It is further proposed that each mental unit, named psychon, is uniquely linked to a dendron. So the mind–brain problem reduces to the interaction between a dendron and its psychon for all the 40 million linked units.

In my 1986 paper (*Proc. R. Soc. Lond. B* 227, 411–428) on the mind–brain problem, there was developed the concept that the operation of the synaptic microsites involved displacement of particles so small that they were within range of the uncertainty principle of Heisenberg. The psychon–dendron interaction provides a much improved basis for effective selection by a process analogous to a quantal probability field. In the fully developed hypothesis psychons act on dendrons in the whole world of conscious experiences and dendrons act on psychons in all perceptions and memories. It is shown how these interactions involve no violation of the conservation laws.

There are great potentialities of these unitary concepts, for example as an explanation of the global nature of a visual experience from moment to moment. It would seem that there can be psychons not linked to dendrons, but only to other psychons, creating what we may call a psychon world.

1. INTRODUCTION

The present paper represents a much further development of a theoretical paper (Eccles 1986). First, it has been possible to identify the basic receptive units of the cerebral cortex, the dendrons, and to incorporate them into the brain–mind theory

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developed on the basis of quantum mechanics. Secondly, it is proposed that the whole mental world is composed of units, psychons, and that mind-brain interaction occurs between the closely linked units, each dendron with its psychon. Thirdly, from these fundamental unitary concepts there will be developed a theory of perception, from dendron activity to psychon experience, also on the basis of quantum mechanics.

2. MIND-BRAIN INTERACTION

It should be recognized that there has been a philosophical revolution since the days of Ryle (1949) and the behaviourists, who denied any scientific meaning to the philosophical concepts of consciousness and to the experiences of self-consciousness. In fact we are in a new era with great interest in the phenomena of consciousness (Searle 1984), even by the materialists (Armstrong 1981; Dennett 1969, 1978; Hebb 1980). However, they feel that their materialist beliefs are not threatened thereby because they regard mental events as existing in an enigmatic sort of identity with neural events at higher levels of the brain, presumably in the cerebral cortex (Feigl 1967). This strange postulate of identity is never explained, but it is believed that it will be resolved when we have a more complete scientific understanding of the brain, perhaps in hundreds of years; hence this belief is ironically termed promissory materialism (Popper & Eccles 1977).

I shall return to the identity theory towards the end of my paper, which is based on an alternative view of the brain-mind problem, namely dualist-interactionism (Popper & Eccles 1977) that is shown in figure 1. The essential feature of figure 1

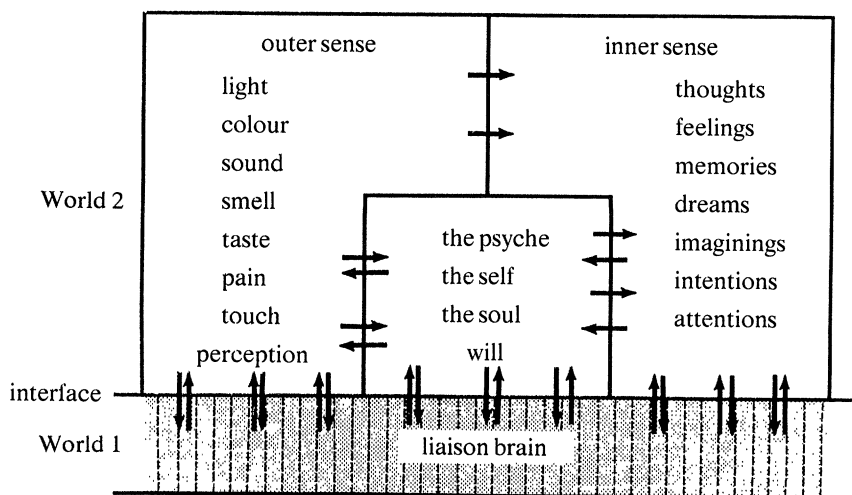


FIGURE 1. Information flow diagram for brain-mind interaction. The three components of World 2 - outer sense, inner sense and the psyche or self - are shown with their connectivities. Also shown by reciprocal arrows are the lines of communication across the interface between World 1 and World 2, i.e. from the liaison brain to and from these World 2 components. The liaison brain has the columnar arrangement of its dendrons, which number about forty million.

is dualism. The whole world of conscious experiences or mind is labelled World 2 and is sharply separated from the brain in the materialist World 1 by an interface. For diagrammatic convenience, World 2 is drawn above the liaison brain in World 1, but actually it would be within the cortex, as shown by the origin and termination of the reciprocal arrows, which signify the interaction across the interface between the two Worlds. This diagram will develop more meaning later in the paper.

3. THE NEURONAL COMPOSITION OF THE CEREBRAL CORTEX

In figure 2 the left cerebral hemisphere is shown in position in the head with some functional areas defined. The essential component is the *cerebral cortex*, which is a cellular layer of about 3 mm thick covering the whole cortex even in its deep

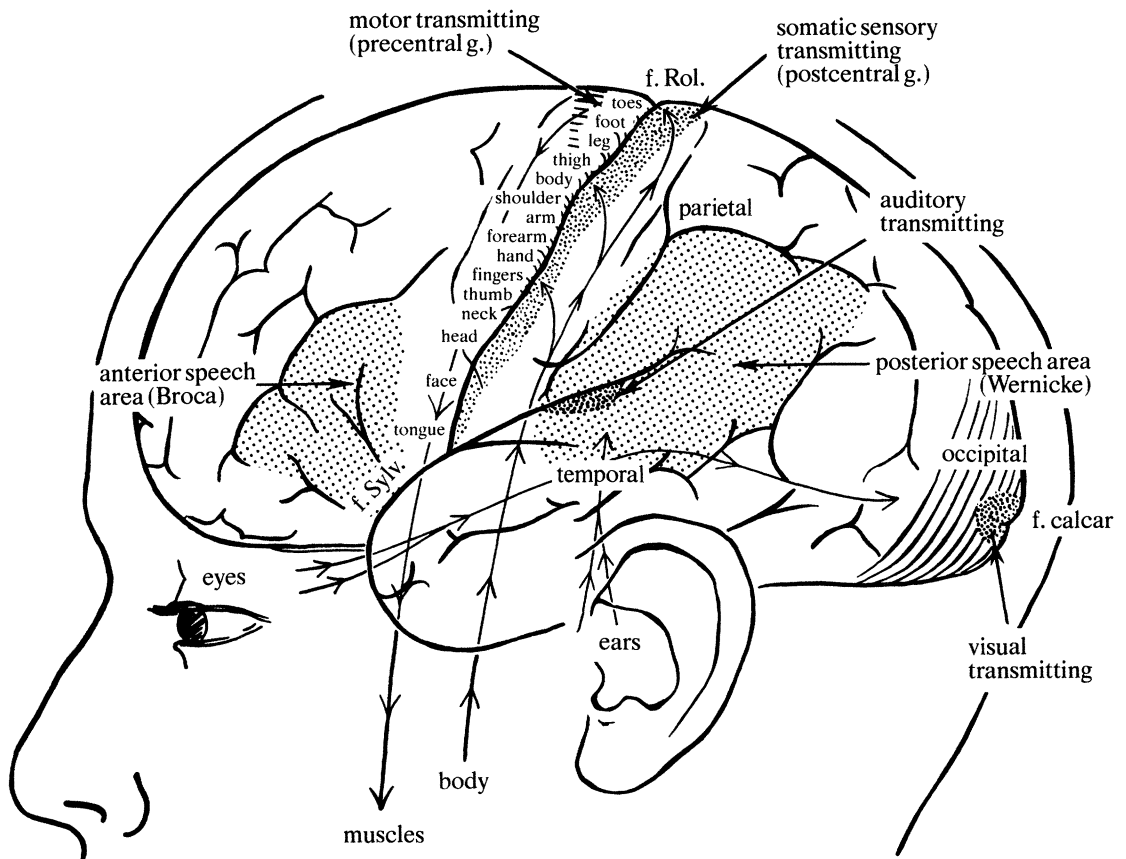


FIGURE 2. The motor and sensory transmitting areas of the cerebral cortex. The approximate map of the motor transmitting areas is shown in the precentral gyrus; the somatic sensory receiving areas are in a similar map in the postcentral gyrus. Actually, the toes, foot and leg should be represented over the top on the medial surface. Other primary sensory areas shown are the visual and auditory, but they are largely in areas screened from this lateral view. Also shown are the speech areas of Broca and Wernicke.

foldings so that it has an area of about 2500 cm² for both hemispheres. The cerebral cortex is created by densely packed nerve cells with their associated nerve fibres, there being about 40000 mm⁻², which would give a total of ten thousand million for the whole cortex. Figure 3*a* illustrates some nerve cells, which were selected from the tangled mass of a Golgi staining and drawn by the great Spanish neuroanatomist Ramón y Cajal. Of special importance are the pyramidal cells E, D, C, B, each with its apical dendrite ascending towards the surface and its axon descending to leave the cortex. At least 60% of cortical cells are pyramidal cells. Figure 3*b* shows three pyramidal cells, one in lamina V and two deep in lamina III.

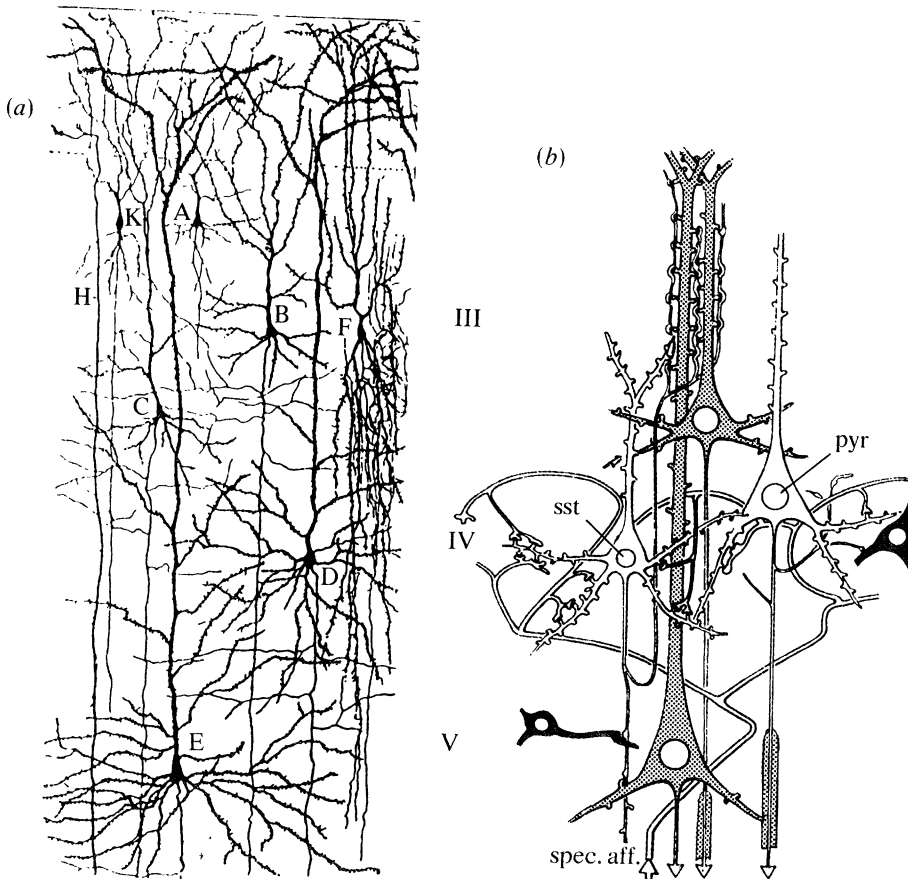


FIGURE 3. Neurons and their synaptic connections. (a) Eight neurons from Golgi preparation of the three superficial layers of frontal cortex from a month-old child. Small (B, C) and medium (D, E) pyramidal cells are shown with their profuse dendrites covered with spines. Also shown are three other cells (F, J, K), which are in the general category of Golgi type II with their localized axonal distributions (Ramón y Cajal, 1911). (b) The direct excitatory neuron circuit of the specific (sensory) afferents (spec. aff.). Both spiny stellate (sst) with ascending main axon, and apical dendrites of both lamina III and V pyramidal cells (stippled) are probably the main targets (Szentágothai 1979).

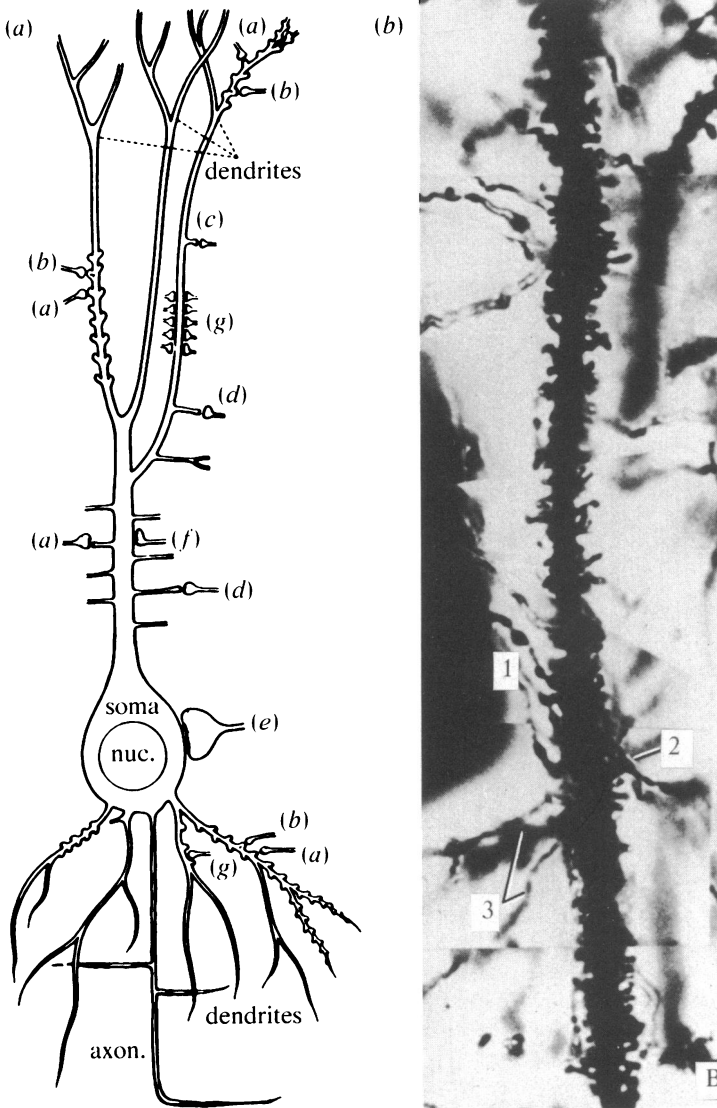


FIGURE 4. (a) Drawing of a hippocampal pyramidal cell to illustrate the diversity of synaptic endings on the different zones of the apical and basal dendrites, and the inhibitory synaptic endings on the soma. (Hamlyn 1963). (b) Mosaic micrographs of apical dendrite of pyramidal cell in the mouse area striata (Valverde 1968).

(Facing p. 436)

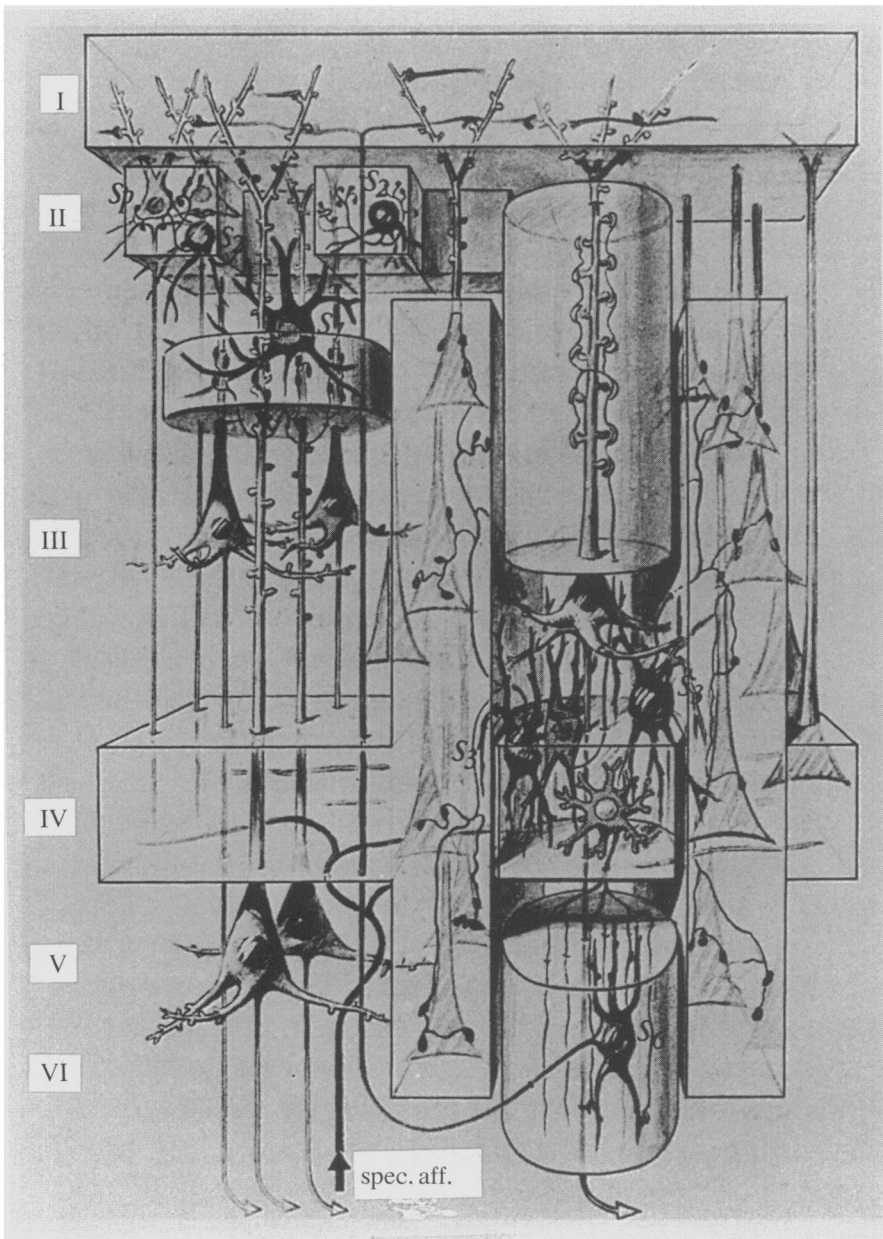


FIGURE 5. Three-dimensional construct showing cortical neurons of various types. There are two pyramidal cells in lamina V and three in lamina III, one being shown in detail in a column to the right (Szentágothai 1975).

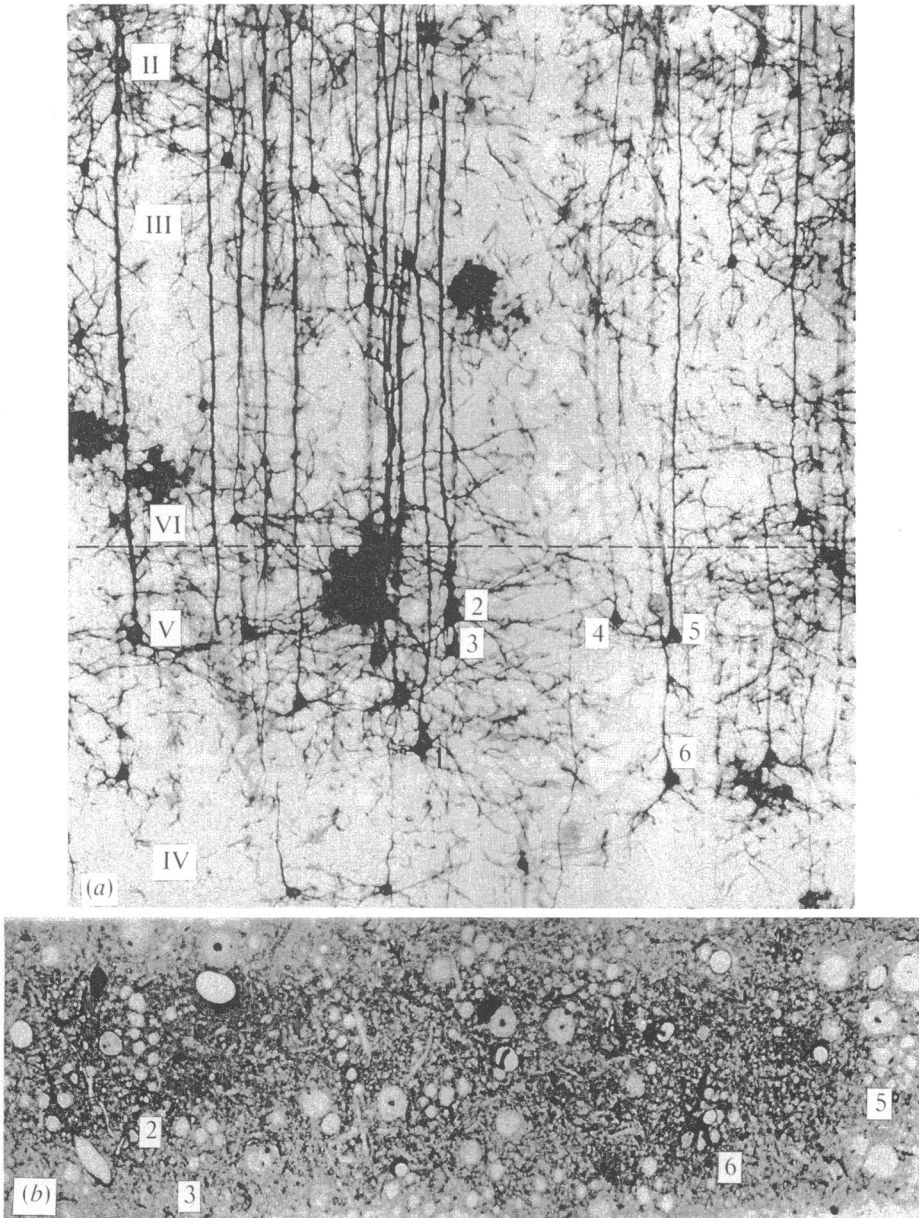


FIGURE 6. (a) Golgi preparation of rat visual cortex (area 17) in a vertical section through laminae II to VI to show apical dendrites of lamina V pyramidal cells projecting through laminae IV, III and II. (b) Tangential section of lamina IV at the level indicated by the broken line in (a). The arrangement of the apical dendrites (small open circles) in clusters can be well seen (Peters & Kara 1987).

DESCRIPTION OF PLATE 4

FIGURE 7. (a) Apical dendritic clusters as visualized in a tangentially oriented section at the level of layer IV of rat visual cortex. One cluster is indicated by open arrows. Calibration line, 25 μm . (b) The large profile is a transversely sectioned apical dendrite within a dendritic cluster, as visualized in a tangential section through layer IV of rat visual cortex. At S, a dendritic spine extending from the apical dendritic shaft forms an asymmetric synapse with an axon terminal. Bar 0.5 μm . (Feldman 1984.)

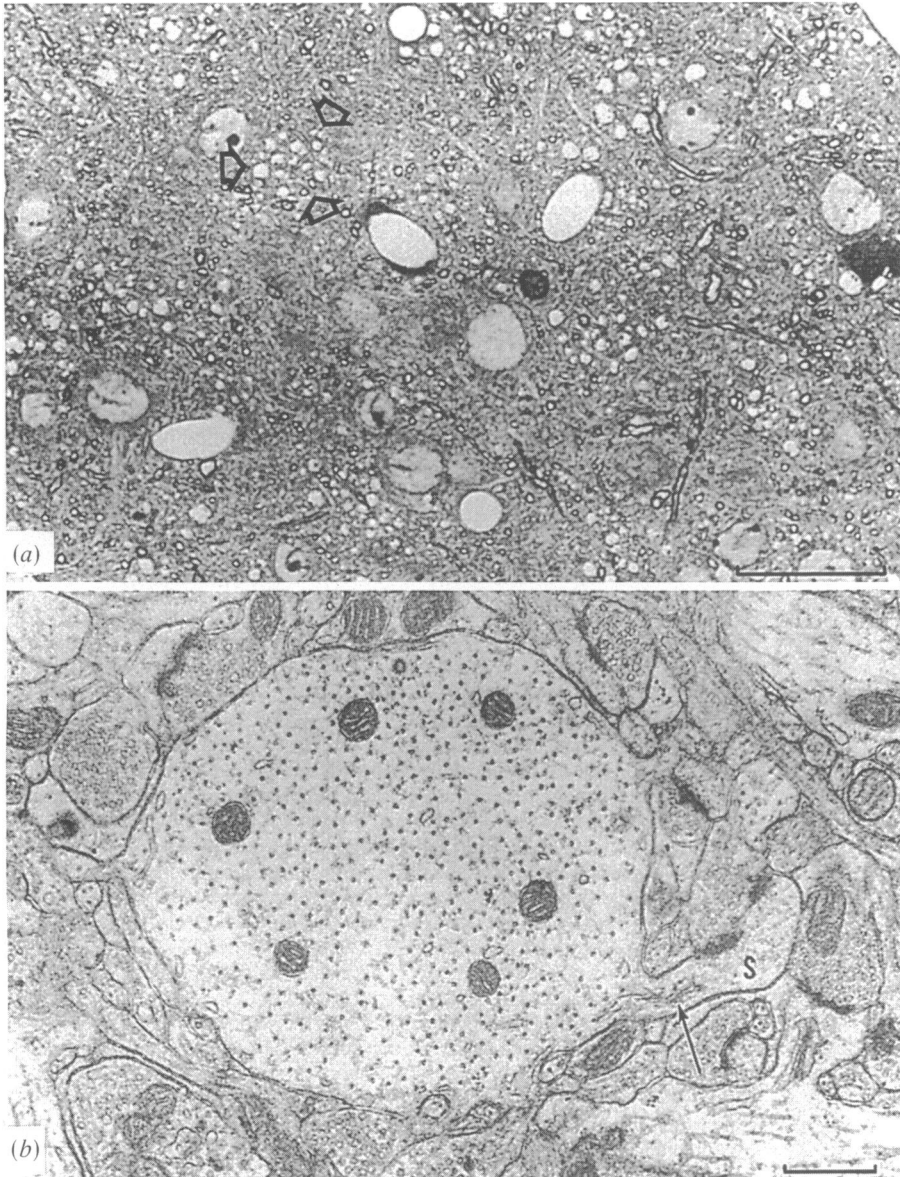


FIGURE 7. For description see opposite.

DESCRIPTION OF PLATE 5

FIGURE 8. Corresponding light and electron micrographs of the same dendritic cluster. Sections taken in the tangential plane at the level of layer IV. In (a) the large apical dendritic profiles considered to form this cluster are indicated by asterisks. In the electron micrograph (b) of the adjacent thin section, these large apical dendrites contributing to the cluster are at least $1.8\ \mu\text{m}$ in diameter. The smaller apical dendrites, $1.0\text{--}1.6\ \mu\text{m}$ in diameter, associated with the cluster are indicated by triangles (Peters & Kara 1987).

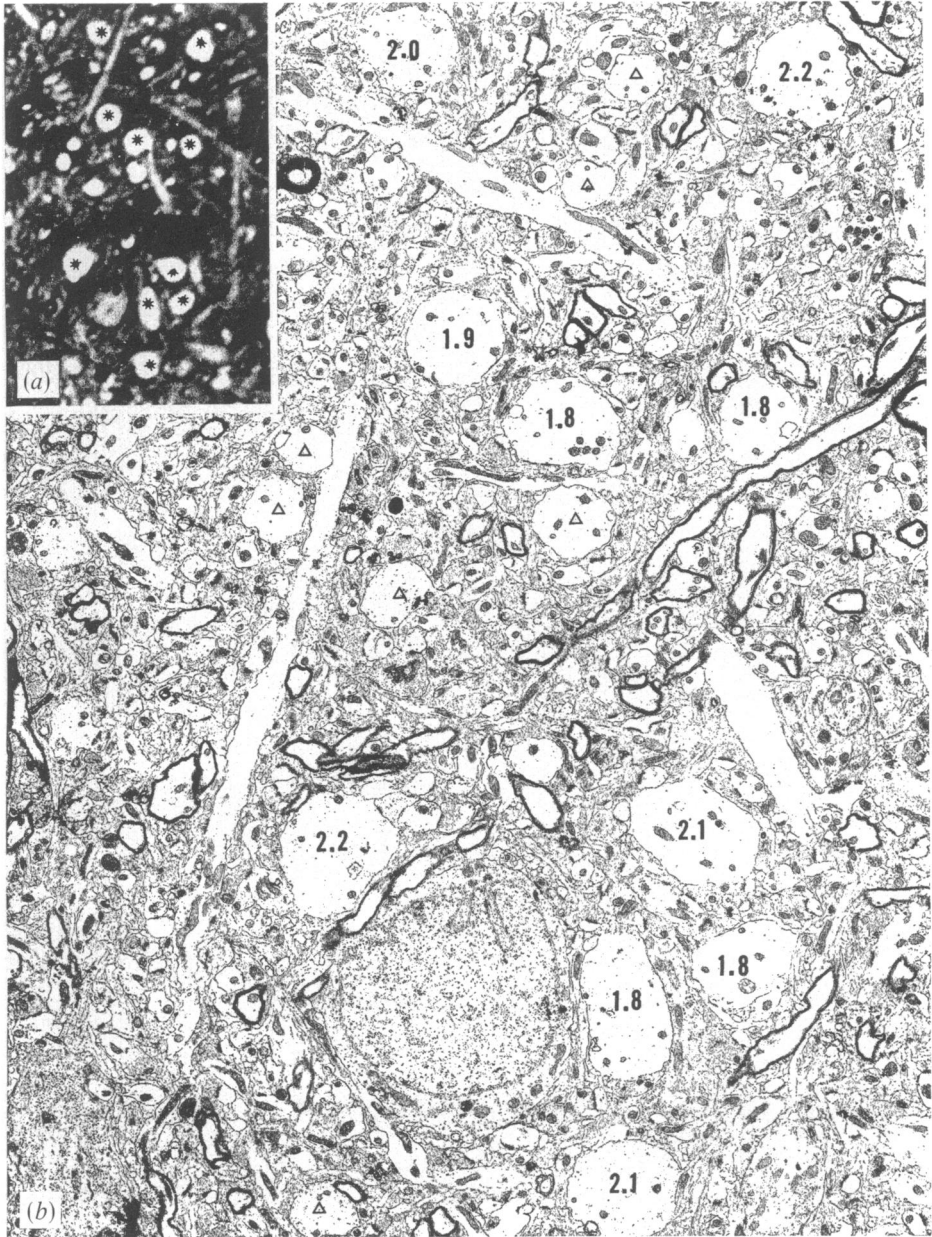


FIGURE 8. For description see opposite.

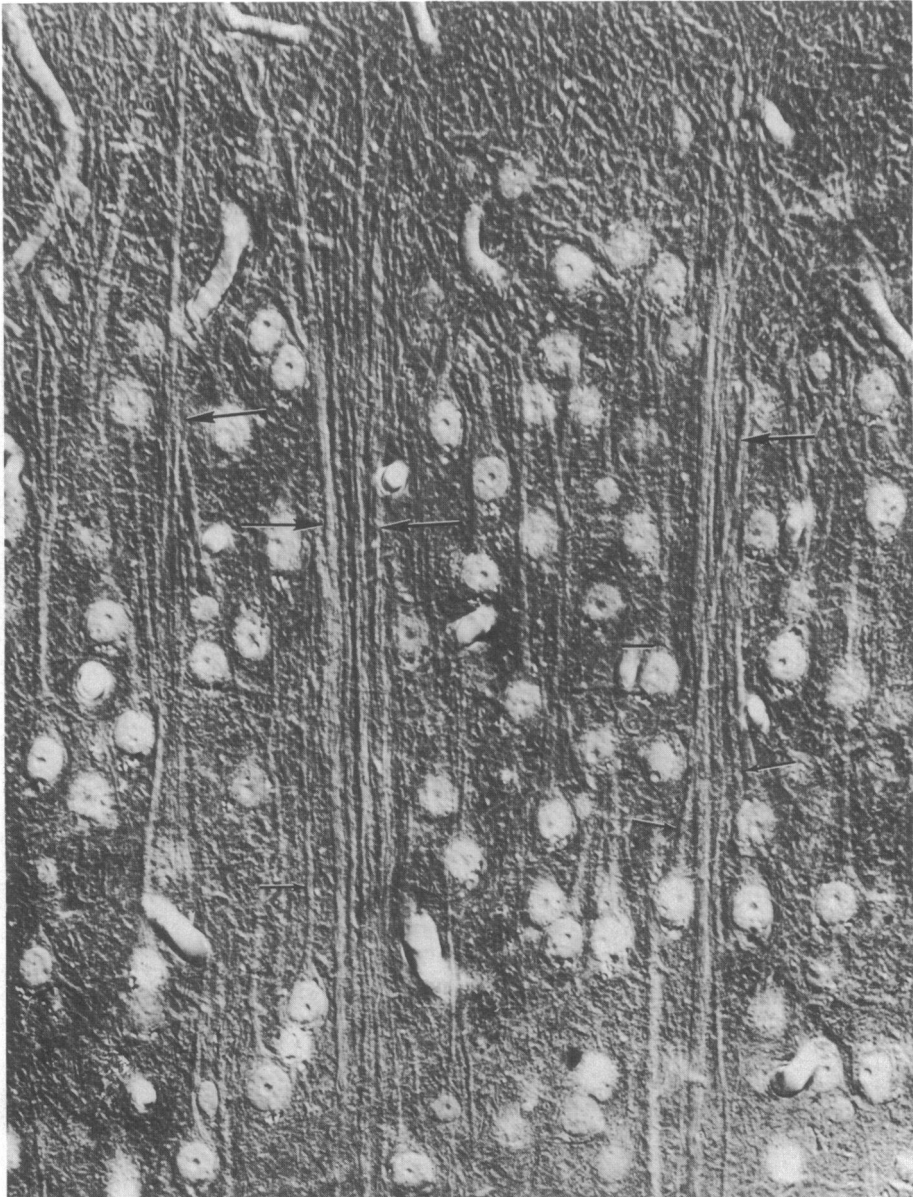


FIGURE 9. Vertical section of the rat visual cortex (area 17) through laminae IV to I to show three clusters of dendrites as indicated by the horizontal arrows. Nomarski optics. Note that apical dendrites of lamina III pyramidal cells add to the clusters (Peters & Kara 1987).

The most important features of pyramidal cells are the small protuberances or spines that already can be seen in the dendrites in figure 3*a* but are more defined in figure 3*b*, where they are seen to be involved in close contacts with nerve fibres, making the spine synapses, which are the principal means of communication between nerve cells in the cortex. A wide variety of spine synapses is drawn in figure 4*a*, plate 1, on a pyramidal cell of a special part of the cerebral cortex, the hippocampus. Finally figure 4*b* shows an apical dendrite from the mouse visual cortex thickly encrusted by spines, which can be counted, there being about one per micrometre and hence at least 2000 for each lamina V apical dendrite with its side branches and tufted ending.

In figure 5, plate 2, there is illustrated the universally accepted six laminae of the cerebral cortex with two large pyramidal cells in lamina V, three in lamina 3 and one (labelled *sp*) in lamina 2. There are many other pyramidal cells shown in shadowy outline and also several non-pyramidal cells, particularly in lamina IV. It will be noted that the pyramidal apical dendrites finish in a tuft-like branching in lamina I.

4. THE BASIC RECEPTIVE UNIT OF THE CEREBRAL CORTEX, THE DENDRON

Despite the intense microscopic study of the cerebral cortex, the basic neuronal assembly was not appreciated until Fleischhauer (Fleischhauer *et al.* 1972) and Feldman & Peters (1974) recognized the tendency of the pyramidal apical dendrites to assemble together in small bundles or clusters in their route to lamina I. Since that time they and their associates have convincingly demonstrated this vertical assemblage of apical dendrites from pyramidal cells in lamina V that were joined in more superficial laminae by the apical dendrites of pyramidal III and II cells (Schmolke & Fleischhauer 1984; Feldman 1984; Schmolke 1987; Peters & Kara 1987).

In the photomicrograph of figure 6*a*, plate 3 a Golgi staining of the rat visual cortex reveals large and medium pyramidal cells of lamina V, six being labelled; 1, 2 large and 3, 4, 5, 6 medium. Each apical dendrite ascends directly through the laminae. The bundles or clusters are not well recognized in figure 6*a* because only a fraction of the pyramidal cells is stained by the Golgi method. However, the apical dendrites of pyramidal cells 1, 2 and 3 can be seen in close apposition. In the transverse section of figure 6*b* at the level of the broken line in lamina IV of figure 6*a*, there are many groups of transversely sectioned dendrites.

In a similar preparation (figure 7*a*, plate 4) many discrete clusters can be seen, one being indicated by the three open arrows. Figure 7*b* shows an electron microscopic (EM) picture of a transversely sectioned apical dendrite with the origins of three spines, the most prominent being labelled with an arrow and S. In an EM transverse picture at lower magnification (figure 8, plate 5) there are apical dendrites of 10 large lamina V pyramidal cells with diameters in micrometres and with apical dendrites of 7 medium sized pyramidal V cells indicated by triangles. In the inset is the same dendritic cluster in light microscopy. Its total dimensions are about 23 μm \times 14 μm . In figure 9, plate 6, Nomarski optics are used to display

several groups of apical dendrites, which are defined by the large arrows. The smaller arrows indicate apical dendrites of lamina III pyramidal cells on the way to join the bundle. The section extends from lamina I at the top to lamina III and shows numerous pyramidal cells of laminae III and II.

Figures 6–9 enable the visualization of the bundles or clusters of apical dendrites. It is most clearly shown in transverse sections in lamina IV (figures 6*b* and 7*a*) before there is the large addition from laminae III and II pyramidal cells (Peters & Kara 1987). As a consequence of this large accretion to the bundle there may be partial confluence of bundles in lamina II. The perspective drawing (figure 10) by Schmolke (1987) gives an excellent picture of the growth of a bundle from lamina V to laminae III–II. Three bundles are shown in the transverse section at the top. Figure 10 is simplified by neglecting the 20–30% of apical dendrites that do not participate in the bundles (Peters & Kara 1987). The average number of apical dendrites participating is about 8 large and 30 medium lamina V pyramidal cells with accretion to a total of 70–100 in lamina II before ending in the apical tufts of lamina I (figures 5 and 9).

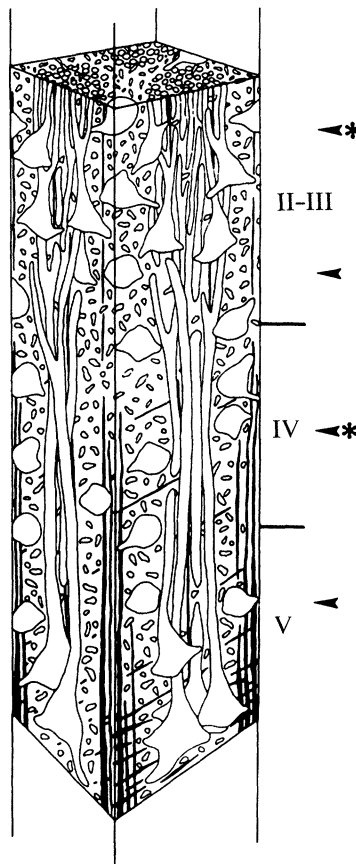


FIGURE 10. Stereoscopic diagram of a portion of rabbit visual cortex comprising laminae II–III, lamina IV and the upper half of lamina V. The distribution of dendrites (white), myelinated axons (black) and perykarya (white) is shown (Schmolke 1987).

There are many small pyramidal cells in laminae IV and VI, but their apical dendrites have a quite different course, ascending only up to lamina III before tufting. They do not join the bundles. Thus about one half of neurons of the cerebral cortex do not participate in the bundles or clusters.

Despite this partial disarray there is agreement by Peters and Fleischhauer and their associates that the apical bundles or clusters diagrammatically shown in figure 10 are the basic anatomical units of the cerebral cortex (Schmolke & Fleischhauer 1984; Peters & Kara 1987). They are observed in all areas of the cortex that have been investigated and in all mammals including humans.

Hitherto there has been no satisfactory suggestion of the functional role of these anatomical units. It is now proposed that they are the cortical units for reception, which would give them a preeminent role; hence it is desirable to name them. Since they are composed essentially of dendrites, the name *dendron* is proposed. In the nineteenth century dendron was an alternative term for dendrites, but it has fallen into disuse in this century. For example, after 1900 it was not used by Ramón y Cajal or by Sherrington. As the proposal is that the dendron is a fundamental neural unit of the cerebral cortex, the ending of 'on' appropriately links it with the units of physics.

Approximate values can be given for the synaptic connectivity of a dendron. The input would be largely by the spine synapses (figures 3*b*, 4*a, b*) which could be over 5000 on a large dendrite, a lamina V apical dendrite with its lateral branches (figure 3(A)) and its terminal tuft, but more usually it would be under 2000. If there are 70–100 apical dendrites in a dendron, the total spine synapses

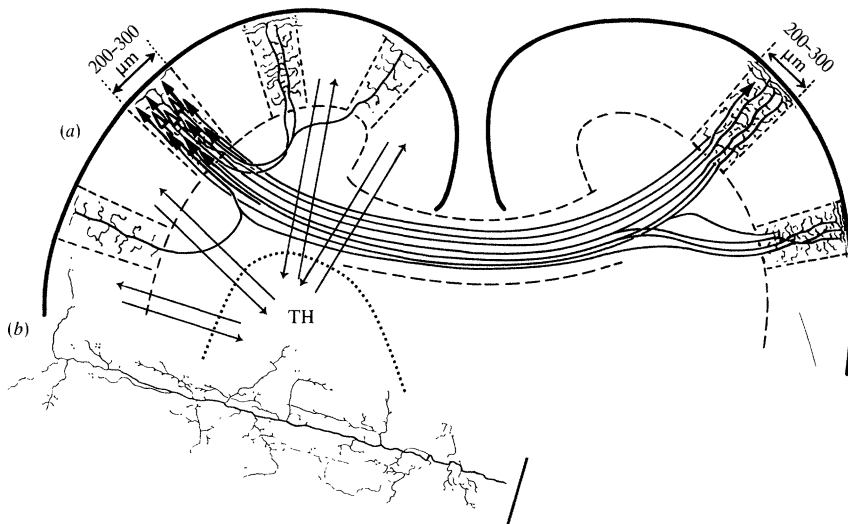


FIGURE 11. (a) General principle of corticocortical connectivity shown diagrammatically in a non-convoluted brain. The connections are established in highly specific patterns between vertical columns with a diameter of 200–300 μm in both hemispheres; TH, thalamus. (b) Golgi-stained branching of a single corticocortical afferent, oriented in relation to the module with a single afferent in (a), but at several times higher magnification. (Szentágothai 1978). Scale bar, 100 μm .

would be over 100 000. In addition to the apical dendrite there are also numerous synaptic inputs to the basal dendrites and soma, as partly indicated in figure 3*b*, but these are mostly inhibitory.

The synaptic output of a dendron is enormous. The axons of the pyramidal cells would mostly be distributed with the modular transmission to the ipsilateral and contralateral cerebral hemispheres, as illustrated schematically in figure 11 (Goldman & Nauta 1977; Szentágothai 1978). It is important to recognize that, as a basic anatomical unit of the cerebral cortex, the dendron has about 200 neurons in its region. The modules are transmission units defined by the corticocortical connectivities of the axons of the pyramidal cells (figure 11) and each would contain about 4000 neurons, which is about 20-times larger than the dendrons. There are about 200 dendrons and 10 modules per square millimetre of the cerebral cortex and about 40 million dendrons for the whole cortex.

5. MENTAL INFLUENCES ON THE BRAIN

When one is at absolute rest in a darkened silent room, it is possible to engage in some specific thinking. For example one can concentrate attention to a finger tip in order to detect a minimal touch that is expected. This attention causes a neural activity in rather large areas of the brain as is revealed by the rCBF technique (regional cerebral blood flow) (Roland 1981). In this technique, radioxenon (^{133}Xe) is injected into the internal carotid artery through a cannula that has been inserted for a clinical investigation. A battery of 254 Geiger counters is mounted in a helmet applied over one side of the scalp. The brief injection causes a pattern of increased radioactivity, as observed by the counts of the Geiger assemblage. This increase in counts signals an increased blood flow, that in turn gives a quantitative measure of the subjacent cortical activity. The counts are done in the control resting situation and then during the chosen mental task, which for figure 12 was concentrated attention on the finger tip in anticipation of a just recognizable touch.

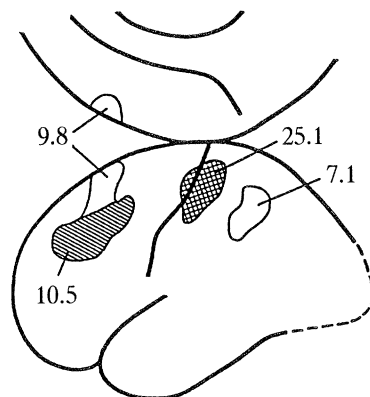


FIGURE 12. Mean increase of rCBF (%) during pure selective somatosensory attention; that is, somatosensory attention without peripheral stimulation. Each individual focus has been transferred to a brain map of standard dimensions with a proportional stereotaxic system. Data from the right and left hemisphere have been pooled. The cross-hatched area has an increase of rCBF significant at the $p < 0.0005$ level. For the other areas shown the rCBF increase is significant at the $p < 0.05$ level (Roland 1981).

There was an increase in the rCBF over the finger-touch area of the postcentral gyrus of the cerebral cortex (figure 12) as well as in the mid-prefrontal and parietal areas. These increases must have resulted from the mental attention, because no touch was applied during the recording. Thus figure 12 is a clear demonstration that the mental act of attention can activate appropriate regions of the cerebral cortex. A similar finding occurs with attention to the lips in expectation of a touch, but of course the activated somatosensory area is now that for the lips. A large prefrontal area was also activated during the anticipation. Each of these areas is an expanse of several square centimetres and would include tens of thousands of dendrons. We can speculate on the mental attention and ask if it has a fine granular composition matching the tens of thousands of dendrons on which it acts.

A complementary investigation was on the mental intention for carrying out a complex learnt series of movements, the motor sequence tests (Roland *et al.* 1980). When the subject was mentally rehearsing the movement sequence without carrying out any movement, there was a large mental activation of the supplementary motor area on both sides. Again we can ask if the mental intention had a fine grain, being recumbent in a dark, quiet room.

Even larger areas of cerebral cortex are activated by complex thinking procedures (Roland & Friberg 1985) such as the successive subtractions of threes from 50, or of the *imagined* experiences in walking along a well-known street, the subject being recumbent in a dark quiet room.

It has to be recognized that the cerebral cortex can store enormous ensembles of memories, hundreds of thousands, and retrieve selectively from this store. So there has to be the potentiality for this enormous storage in the concepts we develop on the mind-brain interaction. In addition the explanatory theory has to be able to account for mind-brain interaction in all the immense diversity of our conscious life.

The hypothesis that dendrons are the neural units of the neocortex leads on to the attempt to discover the mental events which interact with the dendrons in both attention and intention as shown by the reciprocal arrows across the interface in figure 1. At present the experimental evidence (cf. figure 12), is adequate only for establishing that mental intentions and attentions can indeed excite the dendrons, but the observed actions are massive, tens of thousands of dendrons, presumably because of the operation of multitudes of mental events.

6. THE UNITARY LINKAGE OF MENTAL UNITS TO DENDRONS OF THE NEOCORTEX: THE PSYCHON† HYPOTHESIS

As originally expressed the microsite hypothesis (Eccles 1986, p. 426) was deficient in that it did not define precisely the mental events that were assumed

† Professor Garrido has drawn my attention to the fact that M. Bunge has used the word 'psychon' in his book, *The mind-body problem* (Pergamon Press 1980). Its derivation is described on page 37.

However, it is a mistake to derive the word 'psychon' (from the Greek word *ψυχή* soul or spirit (*Oxford English Dictionary*)) for every plastic neural system (Bunge 1980, p. 56), which is a purely materialist concept. What Bunge needs is a word derived from the Greek word *πλαστικός* (that may be moulded), which would be 'plaston'. So Bunge should substitute 'plaston' for 'psychon' and leave 'psychon' for the purely mental usage here proposed.

to be acting on the neural events. They had a rather nebulous character. A radical development is now necessary in order to extend the microsite hypothesis to perception and to the whole range of subjective experiences in the World 2 of figure 1. The new hypothesis is that all mental events and experiences, in fact the entire aggregate of the outer and inner senses of World 2 (figure 1) is a composite of elemental or unitary mental events, which we may call psychons. It is further proposed that each of these psychons is reciprocally linked in some unique manner to its dendron. The dendron is a fixed anatomical structure except for the synaptic plasticity of learning, but functionally there are great variations in intensity of action according to neural inputs. It is similar functionally with the linked psychon, which can be at all levels of mental intensity from zero to a maximum functional linkage with its dendron. Psychons are not perceptual paths to experiences of World 2 (figure 1). They *are* the experiences in all their diversity and uniqueness. It is generally believed that activation of primary sensory areas of the neocortex (figure 2) does not directly deliver conscious experiences. If that is so, on the psychon hypothesis, there would be no psychons on their dendrons.

The linkage has been crudely indicated in figure 1 by the reciprocal arrows across the interface, and now is more precisely drawn in figure 13 in the manner of figure 10. The lamina V apical dendrites are shown for three dendrons in accord with the

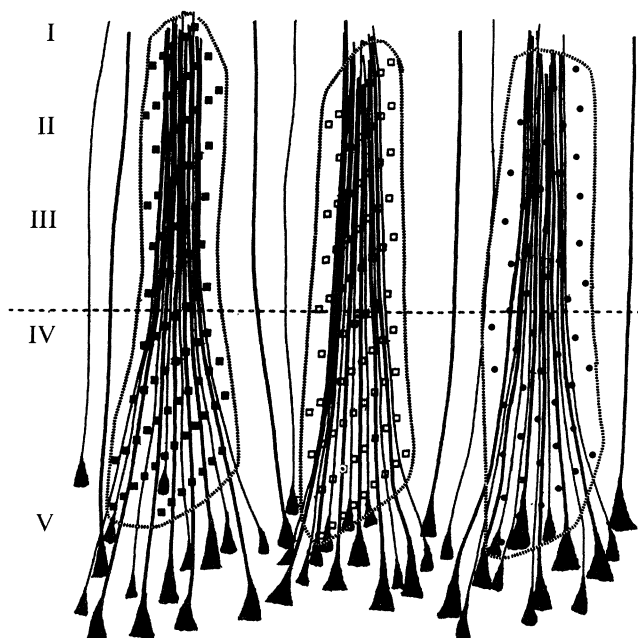


FIGURE 13. Drawings of three dendrons showing manner in which the apical dendrites of large and medium pyramidal cells bunch together in lamina IV and more superficially, so forming a neural unit. A small proportion of apical dendrites do not join the bunches. The apical dendrites are shown terminating in lamina I. This termination is in tufts that are not shown. The other feature of the diagram is the superposition on each neural unit or dendron, of a mental unit or psychon that has a characteristic marking (solid squares, open squares, solid circles). Each dendron is linked with a psychon giving its own characteristic unitary experience.

experimental evidence of figures 6–9. There has even been shown the small proportion of apical dendrites of lamina V that wander and do not join the dendron (Peters & Kara 1987). Superimposed on each of these three dendrons are three psychons, each with its unique psychic character (indicated by squares, open squares and dots) and each embracing the whole dendron. No doubt the congruity is idealized in the diagram, and of course there are multitudes of closely related psychons that could be represented similarly by squares, open squares and dots and that are in unitary relation with similar dendrons. The three different psychons give some insight into the complexity of patterned relation between dendrons and psychons. There could be thousands of types of psychons, each with a matching type of dendron, the grand total being about forty million psychons for the forty million dendrons.

Diagrammatically, when viewed from the cortical surface, each dendron can be illustrated as a circle in close relation with other dendrons, there being about 200 mm^{-2} (figure 14). In this pattern of 64 dendrons the associated psychons are drawn with identification by the same three types of symbol as in figure 13, to give some indication of the patterns of the various dendron–psychon units. Each such ensemble has its own psychic property, for example solid squares for a red light, dots for a touch and open squares for an intention of some specific movement.

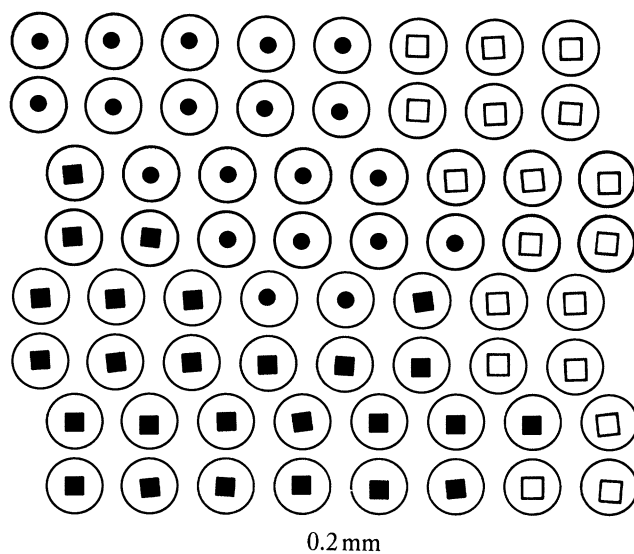


FIGURE 14. Drawing of postulated patterned arrangement of dendrons as seen from the cortical surface. They have the average diameter and spacing (cf. figure 10). Central on each dendron is the symbol of its psychon, solid squares, open squares and solid circles, as shown in figure 13. Note scale of 0.2 mm.

It may seem that in this intimate linkage of dendrons and psychons the new unitary hypothesis of dualist-interactionism is merely a further refinement of the materialist identity hypothesis (Feigl 1967) (see §2). This is a mistake. Independence of existence is accorded to psychons, as is indicated in figure 1. Figure 1 has often been wrongly interpreted because World 2 is drawn above the World 1 of the

brain. This was for diagrammatic convenience. The reciprocal arrows across the interface show that all the World 2 action is in the neocortex.

This proposed unitary linkage between psychons and dendrons (figure 13) leads to many theoretical developments that in turn will lead to the development of experimental testing procedures. Already there is a vast literature in experimental psychology, cognitive psychology and neurophysiology that can be assimilated to this unitary theory of mind–brain interaction. For this paper it is of immediate interest to develop the unitary theory in attempting to explain mind–brain interaction in perception by utilizing quantum mechanics, as has already been done for mental intentions activating dendrons in the SMA (Eccles 1986).

The unitary hypothesis transforms the manner of operation of the intention. If for example, the psychon for the mental intention is represented by the pattern of open squares on the central dendron of figure 13, it can be seen that the intention is acting on the whole dendron with its assembled pyramidal dendrites and their synapses, which could number up to 100 000. So the mental intention would have a large global operation on that dendron. On the unitary hypothesis the psychon would of course operate at each presynaptic vesicular grid (PVG) (see §7) of its dendron in selecting by means of the quantal probability field, a vesicle for exocytosis. However, collectively there could be tens of thousands of such PVG sites on one dendron, so great amplification is ensured by the unitary operation of the linked psychons and dendrons. One has to recognize that in a lifetime of learning the intention to carry out a particular movement would be channelled largely to those particular psychons that are linked to those dendrons of the neocortex (the SMA) that are appropriate for bringing about the required action.

7. THE ACTION OF MENTAL EVENTS ON DENDRONS

Figure 12 shows that the mental events of thinking (psychons) can very effectively activate the neocortex even when no bodily movement is induced. To analyse this action it is essential to define the mode of action of a dendron (figures 10 and 13) with large ensembles of apical dendrites of pyramidal cells (figures 6–10), each with about one spine synapse per micrometre (figure 4*b*), so that there can be 100 000 spine synapses on a dendron. The apical dendrites of a dendron are usually closely associated, but not touching (figure 8), although their spines (figure 4*a*) may interlace (Feldman 1984).

Figure 15 gives a diagram of a spine synapse showing the nerve fibre expanded to a terminal bouton that makes a close contact with a special membrane thickening of the spine. In the bouton are numerous vesicles, each of which contains 5000 to 10 000 molecules of the specific synaptic transmitter substance, which is glutamate or aspartate for the great majority of excitatory boutons in the cerebral cortex. Some synaptic vesicles are in close contact with the presynaptic membrane confronting the postsynaptic membrane across the extremely narrow synaptic cleft. These synaptic vesicles appear to be arranged between dense projections.

Further structural analysis, particularly by the freeze–fracture technique of Akert *et al.* (1975), has led to the construction of a diagram of an idealized spine synapse (figure 16*a*), which is shown in perspective with partial excisions to reveal

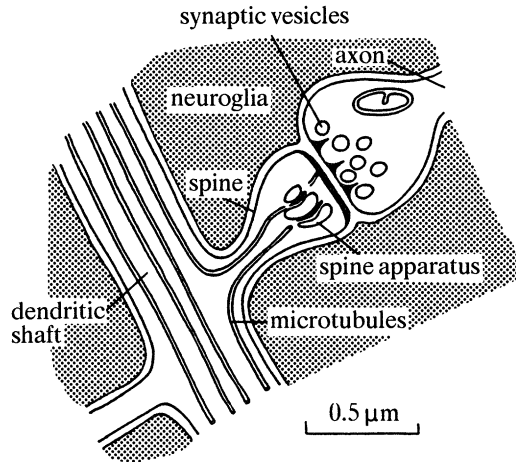


FIGURE 15. Drawing of a synapse on a dendritic spine. The bouton contains synaptic vesicles and dense projections on the presynaptic membrane (Gray 1982).

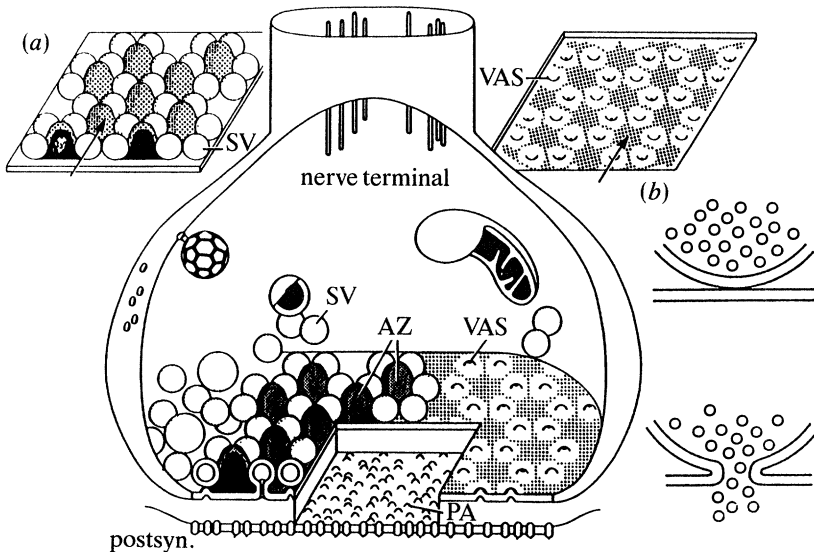


FIGURE 16. Schema of the mammalian central synapse. The active zone (AZ) is formed by presynaptic dense projections spacing synaptic vesicles (SV). PA, particle aggregations of postsynaptic membrane (postsyn). Note synaptic vesicles in hexagonal array, as is well seen in the upper left inset, and the vesicle attachment sites (VAS) in the right inset. Further description in the text (also see Akert *et al.* (1975)). (b) Stages of exocytosis with release of transmitter into the synaptic cleft (Kelly *et al.* 1979).

the deeper structures. The relatively loose arrangement of synaptic vesicles and presynaptic dense projections (figure 15) is replaced in figure 16a as the precise packing illustrated in the inset on the left, with the synaptic vesicles in hexagonal array packaged between the presynaptic dense projections in triangular array. This composite structure is termed a presynaptic vesicular grid (PVG) and it can

be regarded as having paracrystalline properties. The boutons of brain synapses have usually a single PVG, as indicated in figures 15 and 16*a*.

There are only approximate figures for the number of synaptic vesicles incorporated in a PVG. The usual number appears to be 30–50. Thus only a very small proportion of the synaptic vesicles of a bouton (about 2000) are embedded in the firing zone of the PVG. The remainder are loosely arranged in the interior of the bouton, as is partly illustrated in figures 15 and 16*a*.

Figure 16*b* shows at high magnification a part of a synaptic vesicle with its contained transmitter molecules in contact with the presynaptic membrane, as is also seen for two vesicles to the left of figure 16*a*. Below is the process of exocytosis with release of the transmitter molecules into the synaptic cleft, as is also seen for one vesicle in figure 16*a*. To the right of figure 16*a*, after the vesicles and the dense projections have been stripped off, the vesicle attachment sites (VAS) are seen in hexagonal array, as is also seen in the inset diagram to the right.

When a nerve impulse invades a bouton (figures 15 and 16), the depolarization causes the entry of Ca^{2+} ions that combine with calmodulin and that may act on an apposed vesicle to trigger an exocytosis. As indicated in figure 16*a*, there may be 30–50 vesicles incorporated in the PVG, yet in response to a triggering impulse, only one sometimes suffers exocytosis (Jack *et al.* 1981; Korn & Faber 1987). Evidently the exocytosis is subject to control by some unknown holistic property of the paracrystalline PVG.

8. A NEW HYPOTHESIS OF MIND–BRAIN INTERACTION BASED ON QUANTUM PHYSICS: THE MICROSITE HYPOTHESIS

The materialist critics argue that insuperable difficulties are encountered by the hypothesis that immaterial mental events such as thinking can act in any way on material structures such as neurons of the cerebral cortex, as is depicted in figure 1. Such a presumed action is alleged to be incompatible with the conservation laws of physics, in particular of the first law of thermodynamics. This objection would certainly be sustained by the nineteenth-century physicists and by neuroscientists and philosophers who are still ideologically in the physics of the nineteenth century, not recognizing the revolution wrought by quantum physicists in the twentieth century.

In formulating more precisely the dualist hypothesis of mind–brain interaction, the initial statement is that the whole world of mental events (World 2) has an existence as autonomous as the world of matter–energy (World 1) (figure 1). The present hypothesis does not relate to these ontological problems, but merely to the mode of action of psychons on dendrons, that is to the nature of the downward arrows across the interface in figure 1.

As stated in the earlier publication (Eccles 1986), it is possible to resolve this impasse because the structures concerned in synaptic transmission are so extremely small that they can be operated analogously to the probability fields of quantum physics as described by Margenau (1984). The essential movement in exocytosis is to open a channel, as illustrated in figure 16*b*. It can be calculated that this involves the displacement of a particle of about 10^{-18} g, and not the much

larger synaptic vesicle of about 3×10^{-17} g as was originally proposed (Eccles 1986). Moreover, the vesicles are already in position in the presynaptic vesicular grid (figure 16*a, b*) so the exocytosis is not dependent on movement through a viscous medium. The postulated action of a psychon would do no more than select for exocytosis any vesicle already in apposition in the paracrystalline PVG (figure 16*a*) with its holistic control as described above.

It can be concluded that calculation on the basis of the Heisenberg uncertainty principle shows that a vesicle of the presynaptic vesicular grid (figure 16*a*) could conceivably be selected for exocytosis by a psychon acting analogously to a quantal probability field. As indicated in figure 16*b* the energy required to initiate the exocytosis by a particle displacement could be paid back at the same time and place by the escaping transmitter molecules from a high to a low concentration. In quantum physics at microsites energy can be borrowed provided it is paid back at once. So the transaction of exocytosis need involve no violation of the conservation laws of physics.

Before these latest dendron-psychon developments, there was the problem of the order of magnitude of a mental intention that was acting by selection for exocytosis of a single vesicle. A great amplification was essential. However, on the dendron-psychon hypothesis a psychon has as its field for the exocytotic selection the 100000 spine synapses on its dendron (figure 13), which gives a possible amplification of its action by several orders of magnitude. Furthermore, it can be assumed from the enormous numbers of activated dendrons in figure 12 that many adjacent dendrons have closely related psychons, as has been shown in figure 14, where there are assemblages of three distinct varieties of dendron-psychon to form three modules for transmission, as in figure 11.

9. HOW NEURONAL ACTIVITY IN THE SENSORY SYSTEMS COULD EVOKE CONSCIOUS PERCEPTIONS

Hitherto, for the whole of perceptual experiences, there has been no microsite hypothesis. The additional hypothesis for all the upward arrows of figure 2 can be developed in stages. Perception is dependent on a *directed attention*. As seen above in figure 12, a mental attention to some surface of the body activates the neocortical areas specifically related to that area, and also more widely to the frontal lobe. No special hypothesis is needed beyond the microsite hypothesis already developed for the action of intention on the dendrons of the SMA (Eccles 1986), and in §8 above.

The response of the neocortex to attention (figure 12) is preparatory to the transaction whereby dendrons are activated in the perceptual process to produce the perceptual mental events. For example, it can be asked: how can activated dendrons of the tactual system give rise to some specific tactile perception? It is the problem of the reverse arrows from World 1 to World 2 of figure 1 (Eccles 1989).

Let us concentrate on the attentional act whereby psychons are exciting dendrons (figure 12) in accord with the microsite hypothesis. On to that background there is superimposed an activation of the dendrons by some perceptual input, for

example a tactile input, which could specifically excite the apical dendrites of the dendron linked to the right psychon of figure 13 (solid circles) that gives a tactual perception. So that psychon is presented with an increase in its dendron of vesicles available for exocytosis in accord with selection by means of the quantal probability field. The hypothesis is that each such exocytosis is a 'success' for the psychon, which gives a signal that is transmitted into the mental world, World 2 of figure 1.

The sequence for tactual perception would be as follows.

- (i) Background activation by attention to the tactual area (figure 12).
- (ii) Sensory input into the tactual nervous system.
- (iii) Activation in the neocortex of the dendrons of the tactual system.
- (iv) Increased exocytosis from the presynaptic vesicular grids of the pyramidal cells of these dendrons. This gives increased opportunity for selective exocytosis by the linked psychon (cf. figures 13, 14, solid circles), which is in accord with a quantum probability field.
- (v) The increase in vesicular selection by the psychon for touch gives directly the experience of a tactual perception in World 2 and a psychon 'success' signal for transmission and integration in World 2.

All other perceptions of the outer sense in figure 1 can be similarly explained.

This unitary perceptual hypothesis is inadequate because it is limited to specifically linked neural-mental units (figure 13). There is no explanation of the tremendous enigma of the unification of our perceptual experiences. For example, from some dynamic activity pattern of millions of visual psychons we perceive a visual picture with all its qualities and movements. It could be that an explanation may emerge from the psychon integration of the diverse activities of dendrons in stage after stage of the visual processing system.

It would have to be assumed that at each stage the psychons are dependent on the dendrons. Possibly diagrams such as those of figures 13 and 14 are applicable even to the highest levels of the neocortex with its gnostic functions (Eccles 1989, ch. 9). Alternatively, some psychons may be linked only with psychons.

10. THE MENTAL WORLD OF PSYCHONS (WORLD 2)

An extension of the microsite hypothesis of mind-brain interaction (Eccles 1986) has led to some extraordinary developments, which are as yet very tentative. The original microsite hypothesis used quantum physics in explaining how a non-material mental event, an intention to move, can cause microsite activity across the interface between mind and brain, largely in the SMA (Roland *et al.* 1980). The attempt to develop this hypothesis for the mind-brain problem in perception has necessitated a radically new hypothesis.

In the original microsite hypothesis (Eccles 1986) the mental intention acted in accord with quantum physics (Margenau 1984) to select for exocytosis a vesicle of the activated presynaptic vesicular grid (figure 16a). It was a unitary action at a microsite and had to be enormously amplified by assuming that there were thousands of microsites on that dendrite and on dendrites of many adjacent pyramidal cells.

In this present unitary hypothesis the linked dendrons and psychons are central to the act. Thus the mental intention acting through a psychon (cf. figures 13 and 14) has automatically available tens of thousands of activated pvg's with their vesicles awaiting selection.

In the reverse transaction, brain to mind, it is necessary to have an extension of the hypothesis, namely that every time a psychon successfully selects a vesicle for exocytosis (in accord with the quantal probability field) the 'micro-success' is registered in the psychon for transmission through the mental world (World 2 of figure 1). There would, of course, be great amplification when the psychon successfully selected, at about that time, large numbers of vesicles from the tens of thousands of pvg's of its dendron. The 'success' signal of the psychon would carry into World 2 the special experiential character of that psychon for integration into the psychon world.

A tentative explanation may be offered for the observation that an input into the sensory nervous system can give rise to a sensory experience. For example, it explains how a visual input gives rise to a visual experience. Activation of an appropriate dendron of area V4 (cf. Zeki 1973) can be exemplified by the dendron to the left of figure 17. This can result in a 'success' response of a psychon indicated by the pattern solid squares and so to the experience of a red colour. However, for such an experience it is likely that there be 'success' responses in several adjacent psychons, as is indicated by the ensemble in figure 14.

11. GENERAL CONSIDERATIONS

It should be recognized that there is superb design of the dendrons for their receptive function, both neuronal and psychic. It must be accepted that all mammals are conscious beings with some control of their actions and some conscious experiences (Eccles 1989, p. 173). The dendron-psychon interaction is thus essential to their mental life. The human situation is further development with the coming of self-consciousness (Eccles 1989, pp. 203, 218) in which psychons may exist apart from dendrons in a unique psychon world, which is the world of the self (figure 1). There are great unknowns in this postulated world of psychons. Their very nature is to give experiences, and we can only indicate their existence diagrammatically by the site of their dendron action, which is shown as an ensheathing in figure 13.

Transmission of psychon to psychon could explain the unity of our perceptions and of the inner world of our mind that we continually experience from moment to moment: that is, for all of the World 2 experiences illustrated in figure 1, above the interface. This problem has been considered in §10 in attempting to explain the unity of visual experience. Hitherto it has been beyond explanation by any mind-brain theory that multifarious neural events in our cerebral cortex can from moment to moment give us global mental experiences that have a unitary character. We feel central to our experiential world (World 2). This phenomenon is shown in the central core of World 2 in figure 1 with its labelling: psyche, self, soul. Arrows are shown projecting into this central locus from the region of outer sense and inner sense. It raises a fundamental question. Are the experiences of the self also

composed of unitary psychons in the same manner as for perceptual experiences for example? If so, is each of these psychons also linked with its dendron and where in the neocortex are these dendrons? We can further ask if there is a category of organized psychons not linked to dendrons, but only with other psychons, forming a psychic entity apart from the brain.

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