Anatomical evidence for cortical subdivisions based on vertically discrete thalamic projections from the ventral posterior nucleus to cortical barrels in the rat

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A vertical cylinder of cells extending through all 6 neocortical layers has been repeatedly proposed as the elementary functional unit of cerebral cortex. This concept was first clearly stated by Lorente de Nó, with reference to the anatomical organization of neocortex, over 30 years ago. Later Mountcastle introduced the concept of a functional ‘column’ of cortex, based on the response properties of single units in somatosensory cortex. Hubel and Wiesel extended this physiological concept to striate cortex and then provided the first anatomical evidence for discrete subdivisions within striate cortex by mapping the distribution of degeneration which followed lesions of individual layers of the lateral geniculate nucleus. They concluded that the unit in monkey striate cortex, at least with respect to eye dominance, was a long slab-shaped column of cortex rather than the vertical cylinder originally proposed by Lorente de Nó. However, one possible reason for this difference not discussed by Hubel and Wiesel is that the ‘eye preference column’ may not be a unitary structure. Each ‘eye preference column’ may in fact represent a number of cylindrical columns aligned in a row. A central problem with attempting to define the limits of cortical columns in the visual cortex on the basis of the discreteness of thalamocortical projections is the nature of the receptor surface and its central representation. The retinal surface is a continuous surface. The central representation of this receptor surface, the striate cortex, is also a continuous cytoarchitectonic surface without any obvious discontinuities. In sum, neither structure has internal divisions or landmarks with which one can compare axonal connections.

In contrast, receptive field discontinuities exist in the somatosensory system, where in certain species there are highly circumscribed specializations in the receptive surface, such as the mystacial vibrissae. The related cortical differentiation is so dramatic that the cluster of small cells related to each vibrissa has been termed a ‘barrel’ by Woolsey and Van der Loos in their study of mouse somatosensory cortex. The relationship of vibrissae to cortical barrels has been established by electrophysiological mapping of the location of cells in rat somatosensory cortex that can be activated by stimulating one mystacial vibrissa. On the basis of this information and
Fig. 1. Low power photomicrographs (× 50) of Fink–Heimer stained coronal sections demonstrating the anterograde degeneration seen in posterior parietal cortex following unilateral dorsal thalamus removal in the opossum (A), hedgehog (B), eastern grey squirrel (C) and the rat (D). The arrows are placed at the midpoint of the dense layer III-IV projection. The degeneration seen in the rat is particularly dense and broken up into repeating vertical bands separated by regions of little degeneration, which are undoubtedly equivalent to the septa of Woolsey and Van der Loos.
cytoarchitectonic analysis, Woolsey and Van der Loos concluded that barrels are the layer IV correlates of functional cortical columns.

Previous studies from this laboratory on the thalamocortical projections to somatic sensory cortex in the opossum and hedgehog\textsuperscript{7–10} provided a basis with which to compare the same thalamocortical projections in an animal that shows the barrel specialization in somatosensory cortex. Initial experiments indicated a dramatic difference between the projections of the ventral posterior nucleus of the rat and the same projections in the hedgehog and the opossum. The present report demonstrates that in the rat the projections from the ventral posterior nucleus to the posterior parietal cortex conforms to the cytoarchitectonic pattern of the cortical barrels in that degenerating terminals segregate into discrete clusters which fill the cortical barrels. This pattern of degeneration is not present in the opossum, the hedgehog or in another rodent species, the eastern grey squirrel.

The present results are based on the study of 15 rat brains in which bilateral lesions were placed stereotaxically in the ventral posterior nucleus. All lesions were made by a posterior horizontal approach in order to avoid any damage to cortex. After survival of 6, 7 or 8 days, the animals were perfused, the brains were sectioned in the transverse or sagittal plane on a freezing microtome, and every fifth and sixth section stained with the Fink–Heimer procedure\textsuperscript{12} and cresyl violet, respectively. In addition, opossum, hedgehog, eastern grey squirrel and rat cases in which the whole dorsal thalamus had been removed unilaterally were available for study. These large lesions permitted a comparison of the total thalamocortical projections to parietal cortex in the 4 species.

Fig. 1 presents a low power photomicrograph of Fink–Heimer stained sections taken from the posterior portion of somatosensory cortex of the opossum, hedgehog, eastern grey squirrel and rat. There is a marked difference in cytoarchitectural differentiation among these cortical areas and a marked difference in the distribution of degenerated thalamocortical fibers and their terminals. The perikarya composing layer IV in the hedgehog, opossum, and eastern grey squirrel form a uniform lamina, while in the rat they are bunched into barrels. The thalamocortical fiber degeneration in layer IV is a relatively uniform dense band which is barely discernible at low magnification in the opossum (Fig. 1A), the hedgehog (Fig. 1B), or squirrel (Fig. 1C) cortex. In the rat, on the other hand (Fig. 1D), the degenerated axons and terminals are extremely dense and localized into dense clusters like the contents of barrels standing side by side. These dense clusters of degeneration are clearly visible at low magnification. Fig. 2 illustrates a case in which a discrete lesion of approximately 100 \( \mu \text{m} \) in diameter was made in the ventral posterior nucleus of the rat. This low power photomicrograph shows that the degenerated axon terminals are grouped into three clusters. Reconstruction from serial sections of this and other cases suggest that the degenerating axonal projections to a cortical barrel form discrete clusters approximately 250 \( \mu \text{m} \) in diameter. Fig. 3 presents a comparison between a higher power photomicrograph of the degeneration in the same case and a detail of a Golgi drawing of mouse parietal cortex by Lorente de Nö\textsuperscript{11}. Note that several of the features drawn by Lorente de Nö over 50 years ago are clearly evident (see figure legend for further details). These
Fig. 2. Low power photomicrograph (× 50) of a Fink–Heimer stained coronal section. In this case a punctate lesion was made in the ventral posterior nucleus. The photomicrograph illustrates the maximal medial-lateral extent of the degeneration, as well as the fact that the field containing the degenerated terminals can be subdivided into 3 clusters.

Fig. 3. A comparison of a detail of a Golgi drawing of Lorente de Nó with a photomicrograph (approximately × 100) of the degeneration of the same case as Fig. 2. The labels applied by Lorente de Nó to the drawing apply equally well to the photomicrograph: B, layer IV terminal plexus; b, incoming fibers which form the plexus; D, espacio interglomerular or septum.
results suggest that the circumscribed areas of dense degeneration in layer IV are roughly spherical in shape and discontinuous with adjacent densities on all sides. While it has not yet been possible to make lesions that result in degeneration restricted to one barrel, the present results provide strong evidence for a discrete input to each cortical barrel. This, in turn, adds support to the concept that each barrel is related to a single functional column. Woolsey and Van der Loos chose the term ‘barrels’ in order to emphasize a relatively cell-free region surrounded by cell bodies. This type of organization is similar to that seen in invertebrate neural ganglia; that is a ring of cell bodies which surrounds a core of neuropil within which the main integrative functions take place. The density of the terminal degeneration seen in the present study as well as the Golgi study of Lorente de Nó suggests that the ‘hollows’ of the ‘barrels’ (the cores) are areas which are extremely rich in synaptic activity. Each barrel in fact may represent a geometric solution to the problem of packing a maximum number of synaptic sites into a minimum space.

A final point is the absence of barrels and clustered thalamocortical projections in the 3 species with which the rat was compared. These 3 additional species also have vibrissae, yet only the rat exhibits a cortical specialization. However, this does not negate the correlation between barrels and vibrissae; rather, it suggests that the barrels are an extreme specialization for the processing of somatosensory information. Analogous specializations exist in other sensory modalities. For example, of the 4 species compared at the beginning of this report, the eastern grey squirrel is the most visual animal, possessing large frontally placed eyes with a good deal of binocular overlap, and of the 4 species, only the squirrel has a truly striated visual cortex. Striated visual cortex and somatic sensory barrel fields may represent extremes in the differentiation of cortical sensory mechanisms. The structural differences between the striate cortex and the barrel fields are perhaps largely a consequence of the information to be processed in the respective sensory modality. The retina is a continuous receptor surface composed of thousands of receptor elements. Information about the outside world is carried in a pattern across receptive units any one of which has little neural significance. On the other hand, the vibrissal field is a punctate receptor system composed of a relatively few receptor units. The central representation of this system is perhaps constructed in a way which serves to emphasize the neural significance of a given receptive unit.

Note added in proof. In a recent paper Hubel and Wiesel (J. comp. Neurol., 146 (1972) 421–450) have presented an extended analysis of the projections from the dorsal lateral geniculate to striate cortex in the monkey. However, the question of the unitary nature of the ‘eye preference’ or ‘ocular dominance columns’ remains unanswered.

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9 Killackey, H., and Ebner, F., Two different types of thalamocortical projections to a single cortical area in mammals, *Brain Behav. Evol.*, in press.