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COMMENTARY
Radial Columns in Cortical Architecture: It Is the Composition That Counts

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The function of any brain structure depends on its neuronal composition and on the pattern of its extrinsic and intrinsic excitatory and inhibitory synaptic connectivity. In this issue of *Cerebral Cortex*, 3 related papers provide the most comprehensive analysis to date of the cellular and synaptic relationships of a standard cortical column in the somatosensory cortex of the Wistar rat. It is hoped that understanding normal composition of this archetypical cortical column may help to explain its functional operations, expose subtle pathological changes that could cause abnormal sensory and cognitive functions, and provide insight into evolution of the cerebral cortex.

Keywords: cerebral cortex, radial unit, somatosensory area, topographic map

Horizontal layers and vertical columns are undoubtedly the most dominant features of cytological organization of the cerebral cortex. However, in the past 100 years, much more research has been done on organization, function, and pathology of cortical layers than on cortical columns (e.g., Jones and Peters 1984–1998; Rakic 2007). This trend appears to be changing. The variations of cortical columns across cytoarchitectonic fields within and between species are being scrutinized (e.g., Herculano-Housel et al. 2008), and deciphering columnar organization in Connectome projects (not to be confused with the Genome Project), such as Blue Brain, has become highly prominent (Markram 2008). Furthermore, modern imaging methods are capable of visualizing columnar organization in the human neocortex (e.g., McKinstry et al. 2002). In this issue of *Cerebral Cortex*, Bert Sakmann and his colleagues have 3 papers which, together, provide by far the most comprehensive data on neuronal and synaptic composition of cortical columns in the rat's somatosensory ("barrel field") areas yet achieved (Meyer et al. 2010a, 2010b; Wimmer et al. 2010). However, unlike in the architecture of palaces where the shapes and capitals of columns are well defined, in neuroscience the problems start with the definition and delineation of columns.

Everyone agrees that the cerebral cortex is made up of a number of histologically identifiable, horizontal laminae and that in some cases, sublaminar divisions are also present. All would also agree, however, that these laminae and sublaminae do not have knife-edge borders, there being a gradient of change of varying distinctiveness between many of them. These gradients of change are brought about by the arrangement of structures that are invisible in classic Nissl-stained sections, which tend to disperse the somata of the neurons found in that layer. This phenomenon reaches its maximum in the motor cortex in which the small neurons of layer IV, visible in the fetal animal, become so dispersed by the growth of the enormous dendrites of layer III and V pyramidal neurons that the layer appears to have disappeared in the adult. With this comes a greater superficial to deep extent of thalamic terminations than that seen in the primary sensory areas, although here, too, despite common thinking to the contrary, thalamic terminations are not confined to layer IV but extend well into layer III.

Although most of these factors are widely recognized and readily incorporated into schemes of cortical connectivity, there has been far less agreement about the vertical or radial organization of the cortex and especially about what constitutes a cortical "column." This is because cortical columns have tended to be defined in operational terms, that is on the basis of observations made with different techniques or as seen in different preparations, often of a particular animal species (reviewed in Jones 2000; Rakic 2008). As a consequence, some would say that there are so many varieties of cortical columns that no definition of an archetypical cortical column would ever be possible. Currently, one can find references to functional columns, minicolumns, hypercolumns, ontogenetic or embryonic columns, ocular dominance columns, orientation columns, barrel columns, and so forth. These modules or cellular compartments tend to be defined and characterized by developmental, anatomical, or physiological criteria and come from observations made at widely varied levels of resolution or "granularity." Furthermore, the same term can apply to columns that are quite different, the cellular minicolumns of one set of workers are clearly not the same as the physiologically recorded minicolumns of others. Often the only thing that the various columns have in common is that the cortical neurons and/or their interconnections are radially (or vertically) deployed and are related by some common factor, such as embryological lineage, connectivity, or stimulus–response properties.

In introducing the concept of cortical columnar organization for the first time, Mountcastle et al. (1957), basing his definition upon the results of single-unit recordings obtained with microelectrodes that entered the cat's somatosensory cortex orthogonal to its surface and traversed its layers sequentially from superficial to deep and in which he recorded the early repetitive responses of the neurons to brief peripheral stimuli, wrote as follows: " ... neurons which lie in narrow vertical columns, or cylinders, extending from layer II through layer VI make up an elementary unit of organization, for they are activated by stimulation of the same class of peripheral receptors, from almost identical peripheral receptive fields, at latencies which are not significantly different for the cells of the various layers." In noting the changes that occurred in receptive field location and sometimes in the modality of the stimulus to which neurons responded when a microelectrode ran obliquely across the columnar arrays, Mountcastle estimated that the unitary column should be about 0.5 mm in diameter. The

essence of cortical radial organization, at least for the sensory areas, is captured here. The implications are that this kind of column is defined by the terminations of a group of thalamic fibers that arise from a constellation of neurons receiving input from a topographically identifiable zone of the receptive periphery, from specific receptor types within that zone, and that the outputs of the recipient cells in the cortex are vertically arranged so that the first synaptic activity ensuing from their activation spreads almost instantaneously to neurons located in layers above and below them and in a column not much wider than the diameter of the set of place- and modality-specific cells receiving the thalamic input. All of these elements are represented in the 3 papers appearing in this issue of *Cerebral Cortex* (Meyer et al. 2010a, 2010b; Wimmer et al. 2010).

Mountcastle was to extend his findings in the cat to the monkey, in which place- and modality-specific columns of about the same dimensions as those found in the cat were also observed (Powell and Mountcastle 1959; Mountcastle 1997). In a further refinement of this modularity, Favorov et al. (1987) and Tommerdahl et al. (1993) were to describe a subcolumnar organization in which the larger columns defined by input from a patch of skin are composed of minicolumns about 50 μm in diameter, all of whose receptive fields are centered on the same patch of skin but in which there is no predictability about the changes in receptive field size, shape, and especially location of the receptive fields within the larger patch as an electrode moves from one minicolumn to the next. The implication here is that the larger column, although defined by a zone of termination of overlapping thalamocortical axons arriving from a particular topographic location, is made up of minicolumns that represent groupings of vertically arranged neurons innervated directly and indirectly by a unique subsidiary group of those overlapping axons. Here, the minicolumns would be extracting specific information from a vast array of potentially converging thalamic inputs. This aspect of cortical columnar organization is less a feature of the current 3 papers but may have developmental implications that we deal with below.

What the authors of the present set of papers define as a "standard" column in the rat somatosensory cortex is based on the topographically specific input from the large bundle of thalamocortical axons emanating from a single "barreloid" in the ventral posterior medial (VPM) nucleus of the thalamus and terminating in one of the "barrels," the layer IV aggregations of neurons that are features of the rodent somatosensory cortex. In this case, then, their column is of the kind defined originally by Mountcastle and not a minicolumn, although it may contain minicolumns as defined above. Based on measurements of concentrations of thalamocortical axon terminals labeled by green fluorescent protein expressed in their parent cells and extending the width of the periodic densities of terminations, which in layer IV are approximately 300-μm wide, across the depth of the cortex, this column has a cross sectional area of about 121 000 square microns and a depth from pia to white matter of approximately 1840 μm. A second kind of column defined by the authors has its basis in the terminations of axons arriving from the posterior medial (Pom) nucleus of the thalamus and ending deep and superficial to the barrels and especially in the zones of reduced cell density or "septa" lying between them. This column, as measured from septum to septum and across the intervening barrel is thus a little wider than the column defined by inputs to the barrels; it has a cross sectional area of approximately 124 000 square microns but when projected across the depth of the cortex has the same length as the VPM-based column. The measurement of the Pom-based barrel might be rather arbitrary since the authors describe the axons of Pom neurons as spreading horizontally for seemingly wider extends than those from VPM.

One of the strong features of the current set of papers is their quantitative approach which permitted the identification of some 17 000–19 000 neurons in each of the columns defined by the extent of thalamic terminations of the layer IV barrels, with different laminar densities as would be expected from the Nissl-based cytoarchitecture. The density of neurons in the septa was predictably much less. Given this knowledge, it was possible for the authors to estimate the number of action potentials that would be generated in a column by deflection of the single whisker that provides the (multireceptor-based) input to a barrel. In this, the authors touch on the idea that a columnar input can also lead to a columnar-based output, something that has received little consideration in the past, although it has been clear from the earliest myeloarchitectonic studies of the cortex that efferent fibers aggregate in radial bundles that more recent work suggests may reflect the bundling of apical dendrites of pyramidal cells, especially of those in layer V. To what extent these apical dendritic bundles might form a basis of minicolumns of the kind remarked on above has not been determined; but, from the quantitative data presented, there should be about 150 of these per barrel-defined column. Missing from the present analysis is consideration of that other minicolumnar arrangement of cortical axons because it is only present in primates: The repeated bundles of axon collaterals that descend from the inhibitory double bouquet cells of layer II and upper layer III down to the deepest layers, synapsing with the side branches of apical dendrites of pyramidal cells as they do so. DeFelipe et al. (2002) has shown that in monkeys and humans, the double bouquet cell bundles are found in approximately equal numbers and more or less exactly complementary to the radial fasciculi of the pyramidal cell axons. This seems to be yet another basis for thinking that any cortical column based upon the terminations of topographically organized bundles of thalamic axons can be broken down into smaller groupings of cells which retain the fundamental vertical connectivity, such as demonstrated in a more general way in the present set of papers and which may truly be called minicolumns. It will be of special interest to determine if these minicolumnar arrays have their basis in developmental mechanisms or whether they emerge from a more distributed system during development and maturation of the cortex. Given that the thalamic innervation of the rodent barrels occurs by topographically directed growth and does not emerge out of an initial overgrowth that is pruned back (Agmon et al. 1993), we might expect similar directed aggregation of the components of the minicolumns by developmentally guided mechanisms.

A second prominent and important feature of the present papers is their demonstration of the relationships of thalamic axon boutons to the dendrites of injected single neurons in layers II through VI, indicating that not only do virtually all the excitatory neuronal types of the cortex (pyramidal, stellate, and star-pyramidal cells) have dendrites in a position to receive thalamic synapses but also that many of them have innervation domains dominated by inputs from VPM or Pom. This brings to the fore details that had been known to Cajal and other early

(and some recent) neuroanatomists but largely forgotten, namely that thalamic fibers do not restrict their terminations to layer IV or to the spiny stellate neurons in this layer but extend these terminations up into layer III to reach the basal dendrites of layer III pyramids and the apical dendrites of layer V and VI pyramids. To Cajal, it was the pyramidal cell that was at the heart of the circuitry leading from input to output in the cortex, although he recognized that axons ascending vertically from layer IV cells could help to extend the influence of thalamic inputs to other pyramidal cells as well. It was Lorente de Nó (1949) who emphasized the vertical chains of connections ascending and descending across the layers as key components of intracortical circuitry. Cajal was more inclined to emphasize the horizontal collaterals of the pyramidal cells and their presumed role in horizontal intracortical processing. In any case, the terminations directly on pyramidal neurons provide a basis for Mountcastle's original findings that the earliest activation of cells at all depths of the cortical column occurs at closely similar latencies.

The authors of the present 3 papers admit that their efforts at defining the cell types innervated by thalamic afferents is very preliminary. Areas outstanding are to determine the exact nature of the cell types, especially the inhibitory γ-aminobutyric acidergic (GABAergic) cells that receive direct thalamic inputs and also the quantitative nature of the inputs to each cell. Correlative intracellular recording and electron microscopy reveals not only that a single thalamic excitatory postsynaptic potential in a cortical neuron can be sufficient to discharge the cell but also that the number of thalamic boutons received by a cortical cell may in fact represent no more than about 5% of its total complement of synapses (Peters and Payne 1993; Douglas and Martin 2004). Thus, the important quantitative studies reported in the present papers will eventually need to be extended to this new level of resolution.

To what extent and how the various functional columns in the adult cortex, including the somatosensory barrel fields in rat, described by Meyer et al. (2010a, 2010b); Wimmer et al. (2010) and many other types reviewed above, originate during individual development and evolve during evolution only began to be elucidated. However, it is generally agreed that radial organization of the functional columns can be traced to their origin from the neural stem cells and pattern of their migration (reviewed in Rakic 2007). Thus, the terms "embryonic" and "radial or ontogenetic columns" are often used in developmental neurobiology to denote the cohorts of cortical neurons originating from a neuronal progenitor in the proliferative units at the ventricular zone (VZ) (Rakic 1988). The columnar deployment of young, postmitotic neurons is very prominent in the fetal primate cortex, particularly human stained with Nissl methods as well as in electron microscopic serial reconstructions (e.g., Lorente de Nó 1949; Sidman and Rakic 1973; Rakic et al. 1974; Rakic 2007). In addition, the ontogenetic columns are also clearly evident in live slice preparations from developing rodents and other mammalian species (e.g., LoTurco and Kriegstein 1992; Noctor et al. 2001) and can also be traced in vivo using retroviral labeling in embryos of both rodents and primates (Luskin et al. 1988; Kornack and Rakic 1995). Thus, although the exact relationships between embryonic and "functional" columns have not been directly established, they were linked in the "radial unit hypothesis" to explain the origin of columnar organization during development and expansion of the neocortical surface during evolution (Rakic 1988).

According to the radial unit hypothesis, the tangential (horizontal) coordinates of cortical neurons are determined by the relative position of their precursor cells in the VZ, while their radial (vertical) position is related to their time of origin and arrival in the cortex (Rakic 1988 and see animated supplementary movie at: http://rakiclab.med.yale.edu/RadialMigration.html). Therefore, cells within a given radial ontogenetic column originate from progenitors that share the same birthplace in the mosaic (or protomap) of the proliferative zones. Before the onset of corticogenesis, the founder or neural stem cells divide symmetrically, increasing exponentially the number of potential ontogenetic columns in the superjacent cortical plate, indirectly determining the size of the cortical surface in individuals as well as in different species. After their last cell division in the VZ, neurons migrate to the cortical plate along a common radial glial fascicle (Rakic 1972).

Numerous candidate genes and transcription factors have been implicated in modulation of cell division and programmed cell death that affect indirectly the size of the cortical surface and serve as an experimental model of cortical expansion during cortical evolution (e.g., Haydar et al. 1999; Chenn and Walsh 2003; Tarui et al. 2005). How can this hypothesis help understanding development of cytological heterogeneity of functional columns described in the 3 papers in this issue of *Cerebral Cortex*? The heterogeneity is even more evident when one compares cytological organization between columns in different areas within and between species (e.g., Peters 2002). Developmental biologists argue that all columns must consist of polyclones originating from progenitors within the same or adjacent proliferative units as evident from a variety of approaches, including those using transgenic mice (e.g., Rakic et al. 1974, 1995a, 1995b; Tan and Breen 1993; Soriano et al. 1995). Recent studies have identified candidate molecules that may be involved in the proper intermixing of projection neuronal types within cortical columns (Torii et al. 2009). However, columns also contain local circuit or GABAergic interneurons that migrate into the cortex not radially but tangentially via the intermediate zone and layer I, before attaining an appropriate radial and laminar position within a column (e.g., Marín and Rubenstein 2001; Ang et al. 2003; Batista-Brito et al. 2008). Thus, information processing in the cerebral cortex likely depends on radial groupings of pyramidal and local circuit neurons derived from different lineages that are preferentially interconnected (Yu et al. 2009).

The initially crystalline-like appearance of ontogenetic columns in the fetal cortex diminishes over time by their incorporation into larger functional units, the arrival of glial cells, the ingrowth of extrinsic afferents, and the expansions of the dendritic fields especially of the pyramidal cells (Rakic 2007). An abnormal number or an improper mix of neurons in a given column, due to genetic or environmental factors, have been postulated to underlie disorders of higher cortical function (e.g., Gleeson and Walsh 2000; Buxhoeveden and Casanova 2002; Casanova and Tillquist 2008). The valiant effort by the authors of the 3 papers in this issue of *Cerebral Cortex* to reconstruct a "standard column" of the somatosensory cortex in the rat exemplifies the necessity of making extensive reconstructions of the cortex and strongly implies that it will be profitable to extend this approach to other cytoarchitectonic areas in the same, as well as in other mammalian species, particularly the human where columns have a neuronal composition different from those of rodents (e.g., Jones 2009; Rakic 2009). If we are ever to understand how deviation from

normal cellular and synaptic relationships in the cerebral cortex affects the highest brain functions, we have to know the details of the composition of normal columns devoted to different functions. This is not going to be an easy task since such effort may require a greater commitment of time and resources than was devoted even to the Human Genome Project.

Notes

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References

Agmon A, Yang LT, O'Dowd DK, Jones EG. 1993. Organized growth of thalamocortical axons from the deep tier of terminations into layer IV of developing mouse barrel cortex. J Neurosci. 13:5365–5382.

Ang ESBC, Jr, Haydar TF, Gluncic V, Rakic P. 2003. Four-dimensional migratory coordinates of GABAergic interneurons in the developing mouse cortex. J Neurosci. 23:5805–5815.

Batista-Brito R, Machold R, Klein C, Fishell G. 2008. Gene expression in cortical interneuron precursors is prescient of their mature function. Cereb Cortex. 18:2306–2317.

Buxhoeveden DP, Casanova MF. 2002. The minicolumn hypothesis in neuroscience: a review. Brain. 125:935–951.

Casanova MF, Tillquist CR. 2008. Encephalization, emergent properties, and psychiatry: a minicolumnar perspective. Neuroscientist. 14:101–118.

Chenn A, Walsh CA. 2003. Increased neuronal production, enlarged forebrains and cytoarchitectural distortions in beta-catenin overexpressing transgenic mice. Cereb Cortex. 13:599–606.

DeFelipe J, Alonso-Nanclares L, Arellano JI. 2002. Microstructure of the neocortex: comparative aspects. J Neurocytol. 31:299–316.

Douglas RJ, Martin KA. 2004. Neuronal circuits of the neocortex. Annu Rev Neurosci. 27:419–451.

Favorov OV, Diamond ME, Whitsel BL. 1987. Evidence for a mosaic representation of the body surface in area 3b of the somatic cortex of cat. Proc Natl Acad Sci U S A. 84:6606–6610.

Gleeson JG, Walsh CA. 2000. Neuronal migration disorders: from genetic diseases to developmental mechanisms. Trends Neurosci. 23:352–359.

Haydar TF, Kuan C-Y, Flavell RA, Rakic P. 1999. The role of cell death in regulating the size and shape of the mammalian forebrain. Cereb Cortex. 9:621–626.

Herculano-Housel S, Collins CE, Wang P, Kaas J. 2008. The basic nonuniformity of the cerebral cortex. Proc Natl Acad Sci U S A. 105: 12593–12598.

Jones EG. 2000. Microcolumns in the cerebral cortex. Proc Natl Acad Sci U S A. 97:5019–5021.

Jones EG. 2009. The origins of cortical interneurons: mouse versus monkey and human. Cereb Cortex. 19:1953–1956.

Jones EG, Peters A, editors. 1984–1998. Cerebral cortex series. Vol.:1–14. New York: Plenum Press.

Kornack DR, Rakic P. 1995. Radial and horizontal deployment of clonally related cells in the primate neocortex: relationship to distinct mitotic lineages. Neuron. 15:311–321.

Lorente de Nó R. 1949. Cerebral cortex: architecture, intracortical connections, motor projections. In: Fulton JF, editor. Physiology of the nervous system. London: Oxford University Press. p. 288–313.

LoTurco JJ, Kriegstein AR. 1992. Clusters of coupled neuroblasts in embryonic neocortex. Science. 252:563–566.

Luskin MB, Pearlman AL, Sanes JR. 1988. Cell lineage in the cerebral cortex of the mouse studied in vivo and in vitro with a recombinant retrovirus. Neuron. 1:635–647.

Marín O, Rubenstein JL. 2001. A long, remarkable journey: tangential migration in the telencephalon. Nat Rev Neurosci. 2:780–790.

Markram H. 2008. Fixing the location and dimensions of functional cortical columns. HFSP J. 2:132–135.

McKinstry RC, Mathur A, Miller JH, Ozcan A, Snyder AZ, Schefft GL, Almli CR, Shiran SI, Conturo TE, Neil JJ. 2002. Radial organization of developing preterm human cerebral cortex revealed by non-invasive water diffusion anisotropy MRI. Cereb Cortex. 12:1237–1243.

Meyer H-S, Wimmer VC, Hemberger M, Bruno RM, de Kock CPJ, Frick A, Sakmann B, Helmstaedter M. 2010a. Cell type-specific thalamic innervation in a column of rat vibrissal cortex. Cereb Cortex. Advance Access published on June 24, doi:10.1093/cercor/bhq069.

Meyer H-S, Wimmer VC, Oberlaender M, de Kock CPJ, Sakmann B, Helmstaedter M. 2010b. Number and laminar distribution of neurons in a thalamocortical projection column of rat vibrissal cortex. Cereb Cortex. Advance Access published on June 24, doi:10.1093/cercor/bhq067.

Mountcastle VB. 1997. The columnar organization of the neocortex. Brain. 120:701–722.

Mountcastle VB, Davies PW, Berman AL. 1957. Response properties of neurons of cats somatic sensory cortex to peripheral stimuli. J Neurophysiol. 20:374–407.

Noctor SC, Flint AC, Weissman TA, Dammerman RS, Kriegstein AR. 2001. Neurons derived from radial glial cells establish radial units in neocortex. Nature. 409:714–720.

Peters A. 2002. Examining neocortical circuits: some background and facts. J Neurocytol. 31:183–193.

Peters A, Payne BR. 1993. Numerical relationships between geniculocortical afferents and pyramidal cell modules in cat primary visual cortex. Cereb Cortex. 3:69–78.

Powell TP, Mountcastle VB. 1959. Some aspects of the functional organization of the cortex of the postcentral gyrus of the monkey: a correlation of findings obtained in a single unit analysis with cytoarchitecture. Bull Johns Hopkins Hosp. 105:133–162.

Rakic P. 1972. Mode of cell migration to the superficial layers of fetal monkey neocortex. J Comp Neurol. 145:61–84.

Rakic P. 1988. Specification of cerebral cortical areas. Science. 241:170–176.

Rakic P. 1995a. A small step for the cell—a giant leap for mankind: a hypothesis of neocortical expansion during evolution. Trends Neurosci. 18:383–388.

Rakic P. 1995b. Radial versus tangential migration of neuronal clones in the developing cerebral cortex. Proc Natl Acad Sci U S A. 92: 11323–11327.

Rakic P. 2007. The radial edifice of cortical architecture: from neuronal silhouettes to genetic engineering. Special issue on: A century of Neuroscience Discovery: Reflecting on the Nobel Prize to Golgi and Cajal in 1906. Brain Res Rev. 55:204–219.

Rakic P. 2008. Confusing cortical columns. Proc Natl Acad Sci U S A. 105:12099–12100.

Rakic P. 2009. Evolution of the neocortex: Perspective from developmental biology. Nature Review Neurosci. 10:724–735.

Rakic P, Stensaas LJ, Sayre EP, Sidman RL. 1974. Computer-aided three-dimensional reconstruction and quantitative analysis of cells from serial electron microscopic montages of fetal monkey brain. Nature. 250:31–34.

Sidman RL, Rakic P. 1973. Neuronal migration with special reference to developing human brain: a review. Brain Res. 62:1–35.

Soriano E, Dumesnil N, Auladell C, Cohen-Tannoudji M, Sotelo C. 1995. Molecular heterogeneity of progenitors and radial migration in the developing cerebral cortex revealed by transgenic expression. Proc Natl Acad Sci U S A. 92:11676–11680.

Tan SS, Breen S. 1993. Radial mosaicism and tangential cell dispersion both contribute to mouse neocortical development. Nature. 362:638–640.

Tarui T, Takahashi T, Nowakowski RS, Hayes NL, Bhide PG, Caviness VS. 2005. Overexpression of p27 Kip1, probability of cell cycle exit, and laminar destination of neocortical neurons. Cereb Cortex. 15:1343–1355.

Tommerdahl M, Favorov O, Whitsel BL, Nakhle B, Gonchar YA. 1993. Minicolumnar activation patterns in cat and monkey SI cortex. Cereb Cortex. 3:399–411.

Torii M, Hashimoto-Torii K, Levitt P, Rakic P. 2009. Integration of neuronal clones in the radial cortical columns by EphA/ephrin-A signaling. Nature. 461:524–528.

Wimmer VC, Bruno RM, de Kock CPJ, Kuner T, Sakmann B. 2010. Dimensions of a projection column and architecture of VPM and POm axons in rat vibrissal cortex. Cereb Cortex. Advance Access published on May 7, doi:10.1093/cercor/bhq068.

Yu YC, Bultje RS, Wang X, Shi SH. 2009. Specific synapses develop preferentially among sister excitatory neurons in the neocortex. Nature. 458:501–504.