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Monocularly Induced 2-Deoxyglucose Patterns in the Visual Cortex and Lateral Geniculate Nucleus of the Cat: I. Anaesthetized and Paralysed Animals

Siegrid Löwel and Wolf Singer
Max-Planck-Institut für Hirnforschung, Deutschordenstrasse 46, D-6000 Frankfurt a.M. 71, Germany

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Abstract

Extending previous investigations of the topographic relationship between ocular dominance and orientation columns in the cat visual cortex the two systems were visualized with transneuronally transported [^{3}H]proline and with activity-dependent uptake of [^{14}C]2-deoxyglucose, respectively. In addition, we used the 2-deoxyglucose method for a functional assay of both columnar systems. To this end, cats were injected with [^{3}H]proline in the right eye. Two weeks later, they were stimulated monocularly through this eye by presenting contours of only a single orientation in the left and contours of many different orientations in the right visual hemifield while 2-deoxyglucose was injected. The patterns of increased 2-deoxyglucose uptake and of terminal labelling were analysed in flat-mount sections of the visual cortices and in frontal sections of the lateral geniculate nuclei. In the lateral geniculate nucleus, regions of increased 2-deoxyglucose uptake are in register with the [^{3}H]proline-labelled laminae of the open eye. In the visual cortex, the hemispheres stimulated with many different orientations showed a rather homogeneous accumulation of 2-deoxyglucose over the entire extent and throughout all layers of area 17. The hemispheres stimulated with a single orientation displayed columnar patterns of orientation domains essentially similar to those obtained with binocular presentation of a single orientation. In particular and despite monocular stimulation, regions of increased 2-deoxyglucose uptake were neither in register with the [^{3}H]proline-labelled terminals of the stimulated eye in layer IV nor confined to columns of neural tissue above and below these terminals. The maximal horizontal offset between the termination sites of thalamic afferents and activated orientation columns was in the order of 400 μm. These findings suggest several conclusions. (i) In the cat visual cortex, binocular convergence seems to occur so early in cortical processing that monocular stimulation with many orientations leads to a rather homogeneous activation of cortical tissue. (ii) From the termination zones of geniculate afferents activity is apparently distributed already within layer IV to the respective orientation columns. (iii) This horizontal spread of activity could be assured by target cells with radially extending dendrites and/or tangentially oriented fibres.

Introduction

In the feline and primate visual cortex, the afferents conveying signals from the two eyes terminate the discrete regularly spaced clusters in layer IV (Hubel and Wiesel, 1969; Shatz *et al.*, 1977; Shatz and Stryker, 1978; LeVay *et al.*, 1978; Löwel and Singer, 1987a). As the intracortical connections between cells situated in the same vertical column extending orthogonal to the cortical lamination are stronger than those between cells that are displaced from each other horizontally (Lorente de Nó, 1943; Toyama *et al.*, 1981; Gilbert, 1983), neurons within these columns tend to have similar ocular dominance: cells above a cluster of right eye terminals respond more strongly to right than to left eye stimulation and the reverse is true for cells in left eye territories. An interesting mapping problem arises from the fact that cells are also grouped in columns according to their preference for a particular stimulus orientation. In order to obtain an equal distribution of orientation preferences for cells sharing the same eye preference, activity from the respective ocular dominance territories in layer IV has to be distributed evenly to the different orientation columns. The simplest solution would be that each ocular dominance territory comprises a complete set of orientation columns. If this were the case the spacing of columns coding for similar orientations should be the same as the spacing of territories representing the same eye. However, both in cat and in monkey visual vortex, the periodicities of the two columnar systems differ (Hubel *et al.*, 1978; Löwel *et al.*, 1988). There can thus be no fixed spatial relation between ocular dominance territories and orientation columns. The consequence is that activity from a particular eye needs to be relayed tangentially over variable

Correspondence to: Dr Siegrid Löwel, as above

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distances to reach a particular orientation column. There will be cases where a right eye territory happens to coincide with a vertical orientation column but a few cycles away the superimposed orientation columns may be horizontal.

The goal of the present study was to investigate in more detail these relationships between eye dominance and orientation columns in cat visual cortex. To this end we compared in these animals the termination patterns of afferents from the two eyes in layer IV with the activation patterns that result from monocular stimulation with gratings of different orientations. Orientation columns are usually mapped with [^{14}C]2-deoxyglucose (2-DG) (cat: Albus, 1979; Schoppmann and Stryker, 1981; Singer, 1981; Thompson *et al.*, 1983; Albus and Sieber, 1984; Löwel *et al.*, 1987; monkey: Hubel *et al.*, 1977) or more recently with optical recording (cat: Bonhoeffer and Grinvald, 1991; monkey: Blasdel and Salama, 1986) while ocular dominance domains are visualized by labelling the afferents from the lateral geniculate nucleus (LGN) (cat: Shatz *et al.*, 1977; Shatz and Stryker, 1978; LeVay *et al.*, 1978; Löwel and Singer, 1987a; Anderson *et al.*, 1988; monkey: Hubel and Wiesel, 1972). In several studies, these two methods have been combined in order to investigate the topographical relationship between the two columnar systems (Hubel *et al.*, 1978; Löwel *et al.*, 1988). However, one shortcoming of these double-labelling experiments is that an anatomical map is compared with a functional map. In order to study how activity from a particular eye dominance territory is distributed to the various orientation domains it would be appropriate to compare functional maps of eye dominance with functional maps of orientation columns. According to Kossut *et al.* (1983) and Tieman and Tumosa (1983), it is possible to establish functional maps of ocular dominance by 2-DG autoradiography. Monocular but not binocular exposure of freely moving cats to a complex laboratory scene induced columnar patterns of increased 2-DG uptake in area 17 (Kassut *et al.*, 1983; Tieman and Tumosa, 1983). Similar findings have been reported for the monkey striate cortex (Kennedy *et al.*, 1976). We attempted therefore to visualize both orientation and ocular dominance columns with 2-DG and to label the latter in addition with [^{3}H]proline autoradiography. To this end, anaesthetized and paralysed cats were monocularly stimulated in one visual hemifield with contours of many different orientations and in the other with contours of a single orientation. Thus, in the corresponding hemisphere the first stimulus was expected to lead to a complete and exclusive labelling of activated ocular dominance columns while the second was expected to disclose only those fractions of the ocular dominance domains which in addition possess the appropriate orientation preference. For the additional anatomical identification of ocular dominance domains, [^{3}H]proline had been injected into the eye that was stimulated visually. To avoid problems related to serial reconstructions we analysed flat-mounted sections of the visual cortices (Freeman *et al.*, 1987). Some of the results of this study have been published in abstract form (Löwel and Singer, 1987b,c).

Materials and methods

Surgical procedures

The present study is based on three 10- to 12-week-old cats. Two (C1 and C2) were subjected to double-labelling with [^{3}H]proline and [^{14}C]2-DG, one (C3) was investigated only with the 2-DG method (Sokoloff *et al.*, 1977). For transneuronal labelling of ocular dominance columns (Grafstein, 1971), the cats were anaesthetized with a mixture of ketamine hydrochloride (10 mg/kg) and xylazine hydrochloride (2.5 mg/kg) i.m. and then received an injection of 2.5 mCi of [^{3}H]proline (injected volume 50 μl in cat C1 and 25 μl in cat C2) into the right eye. Two weeks later, these cats were prepared for the labelling of orientation domains with [^{14}C]2-DG. A detailed description of our experimental procedures has been published (Freeman *et al.*, 1987; Löwel *et al.*, 1987). Therefore we report only the essential steps of the preparation. Anaesthesia was induced as described above and, after tracheal intubation and cannulation of a femoral vein, was maintained with a mixture of 70% N_2O/30% O_2. The animal's head was fixed in a stereotaxic frame by means of a metal bar cemented to the skull and a muscle relaxant (hexcarbacholinbromide, dose 10 mg in 45 ml of Ringer, 3 ml/kg/h) was applied to prevent eye movements. All wound edges were infiltrated with xylocaine. As with standard electrophysiological recordings the body temperature, ECG, EEG, pulmonary pressure and CO_2 content of the expired air were continuously monitored. End-tidal CO_2 and rectal temperature were kept in the ranges 3–4% and 37–38°C respectively. All animals were stimulated monocularly. Therefore the respective non-stimulated eye (the left eye in cats C1 and C2, the right eye in cat C3) was covered with a black contact lens and an additional black patch. Simultaneously with the onset of light stimulation, the animals received an intravenous injection of 2-deoxy-D-[U-^{14}C]glucose (Amersham, sp. act. 310 mCi/mmol; dose 110–125 μCi/kg), at a rate of 25 μCi/min.

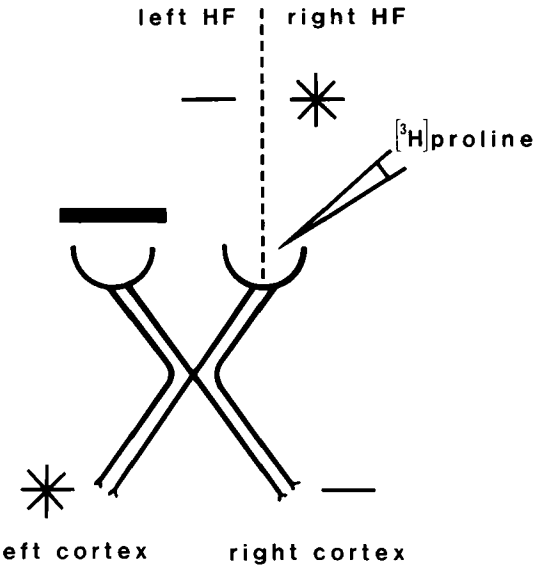


FIG. 1. Schematized drawing of the experimental design. HF = visual hemifield.

Visual stimulation

Cats C1 and C2 were exposed to moving square wave gratings consisting of horizontal contours projected to the left visual hemifield whereas the orientation of the grating projected to the right visual hemifield was changed in 45° steps (Fig. 1). During the first 6 min of visual stimulation each of the four orientations was presented for 1.5 min, then the presentation time was extended to 3 min per orientation for one complete cycle, and finally to 5 min per orientation for the following cycles. In cat C3, only the right visual hemifield was stimulated through the left eye with a horizontal grating sparing 2–3° of the visual field along the vertical meridian.

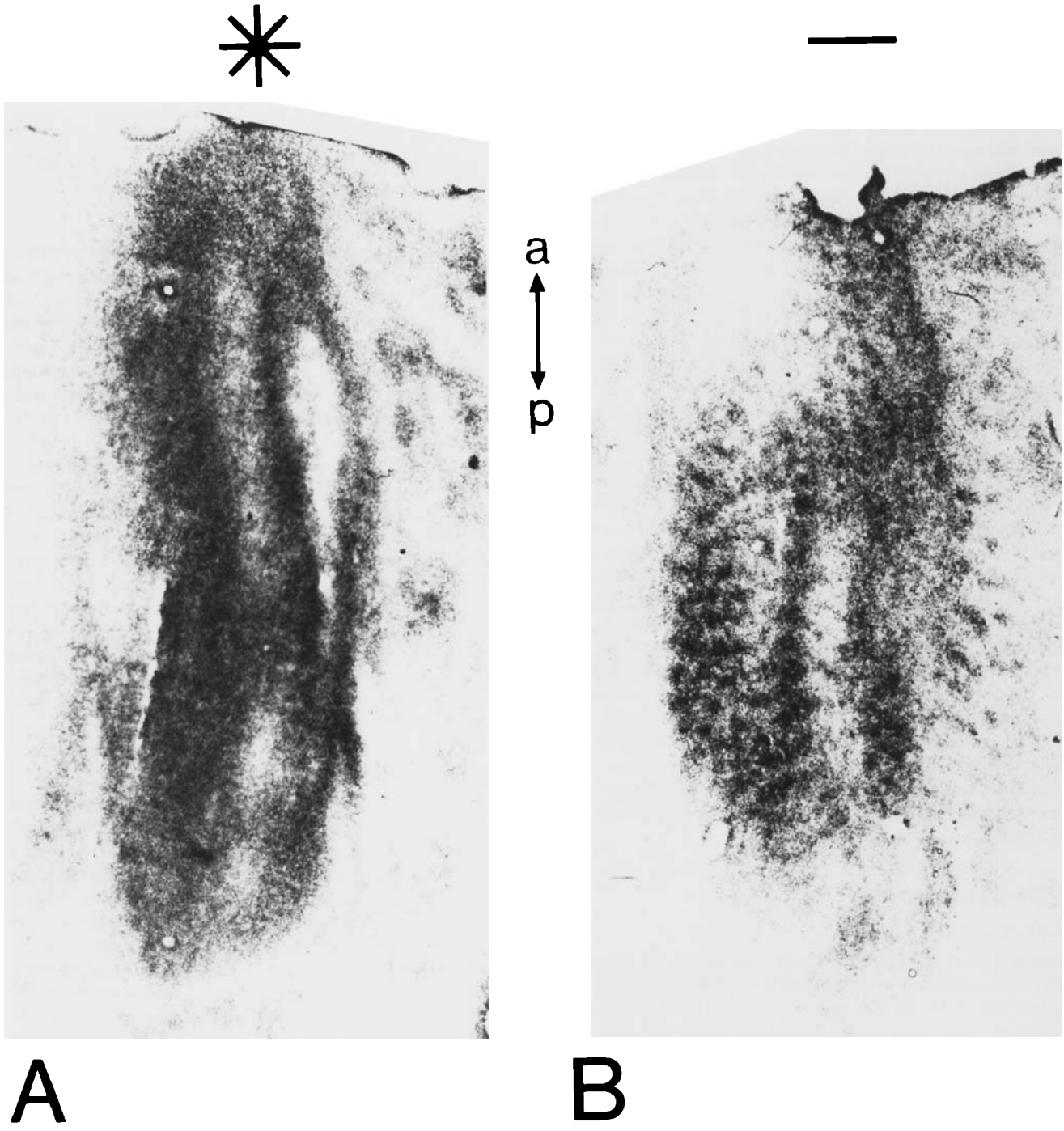
Histological procedures

After 58 min (C1 and C2) or 45 min (C3) of visual stimulation, the animals were given a lethal dose of Nembutal injected intravenously.

The occipital poles and the lateral geniculate nuclei (LGN) of the brain were removed and the visual cortices flat-mounted prior to freezing the tissue on dry ice (Freeman *et al.*, 1987). To provide landmarks for later superposition, three holes were made in the flat-mounts with warm needles. Subsequently, 26 μm thick serial cryostat sections were cut. Blocks containing the visual cortex were cut parallel to the cortical surface; those containing the LGN were cut in the frontal plane. The sections were mounted on glass slides, immediately dried on a hot plate and then exposed to X-ray film (Agfa Mamoray M4) for 3–4 weeks. To visualize the [^{3}H]proline distributions, the same (already mounted) sections were postfixed in 4% paraformaldehyde, washed to remove all [^{14}C]2-DG and then exposed to Ultrofilm (LKB) for 8–12 weeks (Löwel *et al.*, 1988). To control for the possibility that the [^{3}H]proline had contributed to the darkening of the [^{14}C]2-DG autoradiographs, the sections were exposed after washout of [^{14}C]2-DG (after this only ^{3}H should be contained in the sections) a second time to the X-ray films (sensitive to ^{14}C). These controls never revealed any substantial labelling on the ^{14}C films.

Image processing and data analysis

For demonstrating topographical relations between patterns of increased [^{14}C]2-DG uptake and [^{3}H]proline-labelling, the 2-DG and proline autoradiographs were contrast-enhanced with an image processing



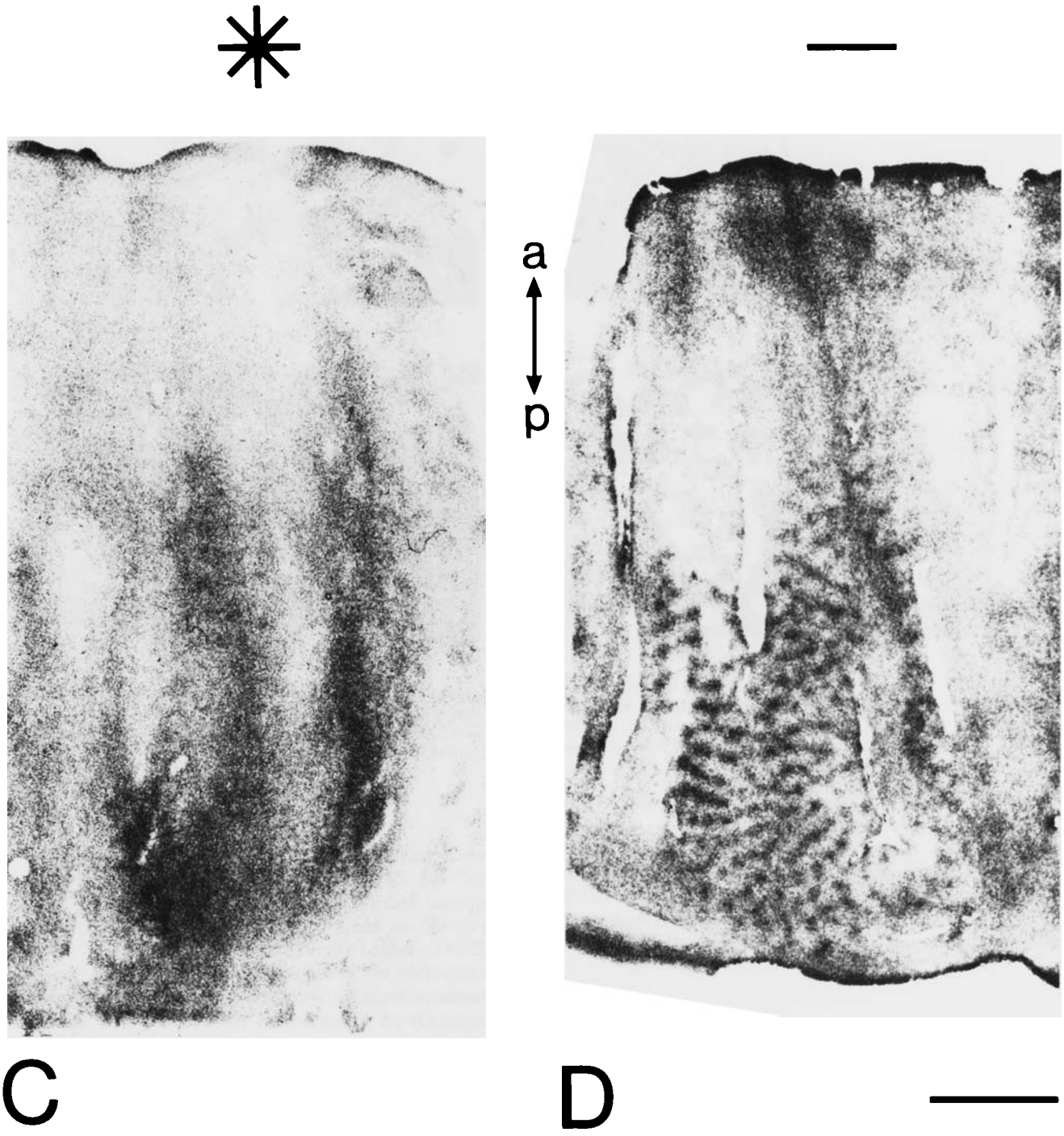


FIG. 2. The distribution of increased 2-DG uptake in the visual cortices of cats C2 (A, B) and C1 (C, D). Autoradiographs of flat-mount sections through layer IV of the left (A, C) and right (B, D) hemispheres that had been stimulated with many different (A, C) or a single orientation (B, D). Note the weak inhomogeneity in 2-DG accumulation in the left visual cortex of cat (C1) (C). Abbreviations: a, anterior; p, posterior. Scale bar, 5 mm.

system (Imago II, Compulog) by expanding the grey values over the full modulation range: regions of lowest 2-DG uptake and proline-labelling (non-injected eye) are displayed in white, regions of highest 2-DG and proline-labelling (injected eye) as dotted (grey) and black profiles, respectively. Large-scale inhomogeneites in the optical density distributions (i.e. uneven illumination of the autoradiographs) were compensated by high-pass filtering the digitized images of the autoradiographs. Contrast-enhanced 2-DG and proline autoradiographs of the same section ('corresponding autoradiographs') were then superimposed graphically with the aid of the needle holes and other landmarks such as blood vessels and air bubbles. Since [^{3}H]proline-labelling is only visible in layer IV of visual cortex (and very weakly also in layer VI; see LeVay and Gilbert, 1976) whereas the [^{14}C]2-DG patterns always extend through all cortical layers, sections of layer IV were selected for comparison of patterns in the same section.

To evaluate further the topographical distribution of peaks of labelling

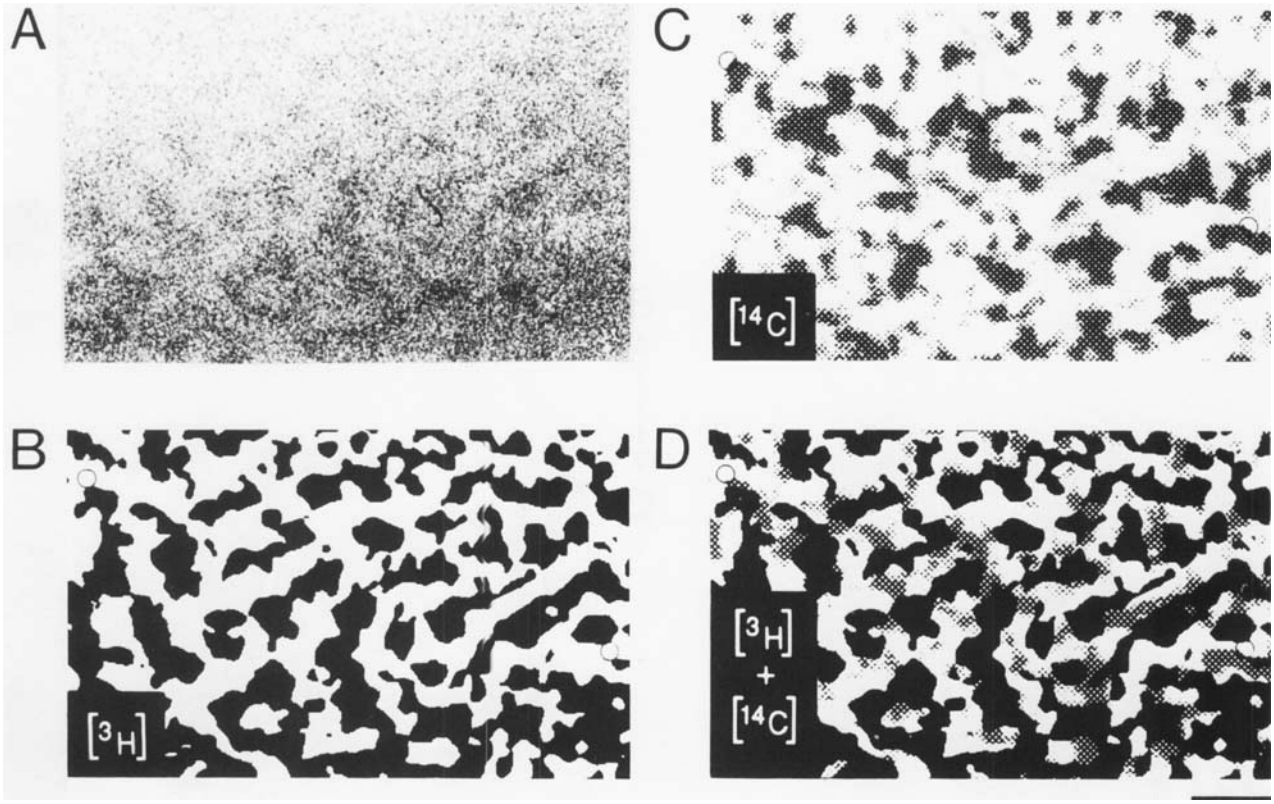


FIG. 3. Patterns of [^{3}H]proline-labelling (A, B) and [^{14}C]2-DG uptake (C) in the same section through layer IV of the left visual cortex of cat C1 (taken from the region with the weak inhomogeneities in 2-DG accumulation in Fig. 2C). (A) Original [^{3}H]proline autoradiograph. (B, C) Contrast-enhanced patterns of [^{3}H]proline-labelling (B, black profiles) and [^{14}C]2-DG uptake (C, halftone dotted profiles). (D) Superimposition of (B) and (C). Dotted profiles correspond to regions of increased 2-DG uptake that do not match with regions of increased [^{3}H]proline-labelling. Scale bar, 1 mm.

in the autoradiographs, optical densities were measured along vectors in selected pairs of corresponding 2-DG and proline autoradiographs derived from the same flat-mount sections (Löwel and Singer, 1987a). Additionally, the mean spacing of adjacent columns was determined by one-dimensional Fourier analyses (Löwel *et al.*, 1987).

Results

Contrary to our expectations, monocular stimulation with many different orientations resulted in a rather homogeneous accumulation of [^{14}C]2-DG radioactivity over the entire extent and throughout all layers of area 17 (Fig. 2A and C). Only in the central region of the left area 17 of cat C1 (Fig. 2C) were some band-like inhomogeneities of 2-DG labelling apparent. To analyse whether these inhomogeneities reflect ocular dominance domains we compared corresponding ^{14}C and ^{3}H autoradiographs, i.e. autoradiographs derived from the same sections. Superimposition of the two patterns revealed that the 2-DG inhomogeneities do not seem to be related to ocular dominance domains (Fig. 3). Despite some degree of overlap, peaks in 2-DG accummulation and proline-labelling do not coincide and sometimes even lie out of register (dotted profiles in Fig. 3D). Thus, even within layer IV regions of increased 2-DG uptake are not restricted to the ocular dominance domains of the stimulated eye.

Another observation is that the spacing of the ocular dominance domains differs from that of the 2-DG columns. To quantify this difference in spacing, we analysed the spectral content of the two patterns along vectors perpendicular to the main trajectories of the 2-DG 'bands' and the ocular dominance domains. The resulting one-dimensional Fourier spectra differ for the ^{3}H and the ^{14}C patterns and peak at 850 μm and 1100 μm, respectively (Fig. 4A). Hence, the [^{14}C]2-DG pattern in the left area 17 of cat C1 is clearly different from that of the ocular dominance domains and rather resembles that of orientation domains (Löwel *et al.*, 1987). The difference in spacing and especially the non-coincident distribution of ^{3}H- and ^{14}C-labelled domains is also visible in optical density measurements along identical vectors in the ^{3}H and the ^{14}C autoradiographs (Fig. 5A): There is no consistent relationship between the peaks and troughs in the 2-DG and proline autoradiographs.

Monocular stimulation with a single orientation induces [^{14}C]2-DG patterns similar to those obtained with binocular stimulation (compare Figs 2B and D and 6A with 6B). Also in the monocular cases regions of increased radioactivity extend throughout all cortical layers and tend to form elongated 'bands'. Their average spacing is in the order of 1 mm (Fig. 4B and C) and thus also differs from that of the ocular dominance domains labelled in the same sections (Fig. 4B). These monocularly induced 2-DG columns also show the periodic variation of 2-DG uptake, previously described as 'beads' in orientation bands (Löwel *et al.*, 1987). Hence they possess all organizational features ascribed to orientation domains. To facilitate a direct comparison between monocularly and binocularly induced patterns, we additionally illustrate the 2-DG pattern of a binocular case (Fig. 6B; adapted from Löwel *et al.*, 1987).

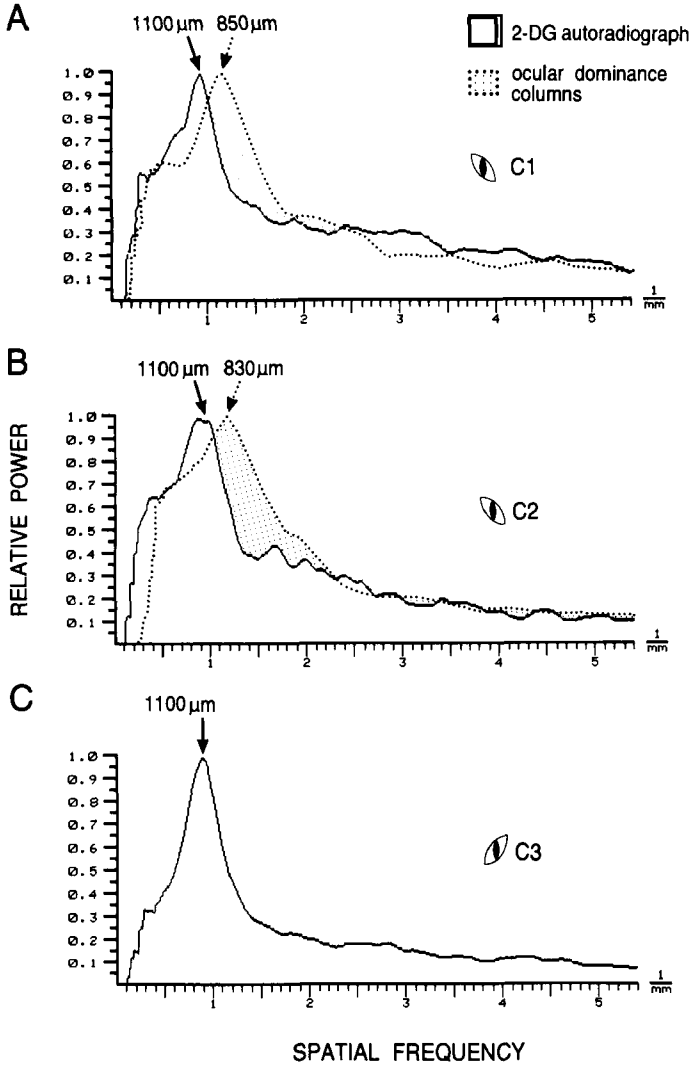


FIG. 4. One-dimensional Fourier analyses of the [^{3}H]proline and [^{14}C]2-DG patterns. The x-axis represents the spatial frequency in cycles/mm, the y-axis the relative power of spectral components. All graphs represent averages of measurements along 25 parallel vectors perpendicular to the main trajectories of the ocular dominance domains and/or 2-DG 'bands'. (A, B) Spatial frequency spectra of the [^{3}H]proline (dotted line and profile) and [^{14}C]2-DG patterns (solid line) in the left visual cortex of cat C1 which was stimulated with many different orientations (A) and in the right visual cortex of cat C2 which was stimulated with a single orientation (B). In cat C1, the spatial frequency spectra of the ^{3}H and the ^{14}C patterns peak at 850 and 1100 μm, and in cat C2 at 830 and 1100 μm. (C) Spatial frequency spectrum of the [^{14}C]2-DG pattern in the left hemisphere of cat C3 which was stimulated with a single orientation. The spectrum peaks at 1100 μm.

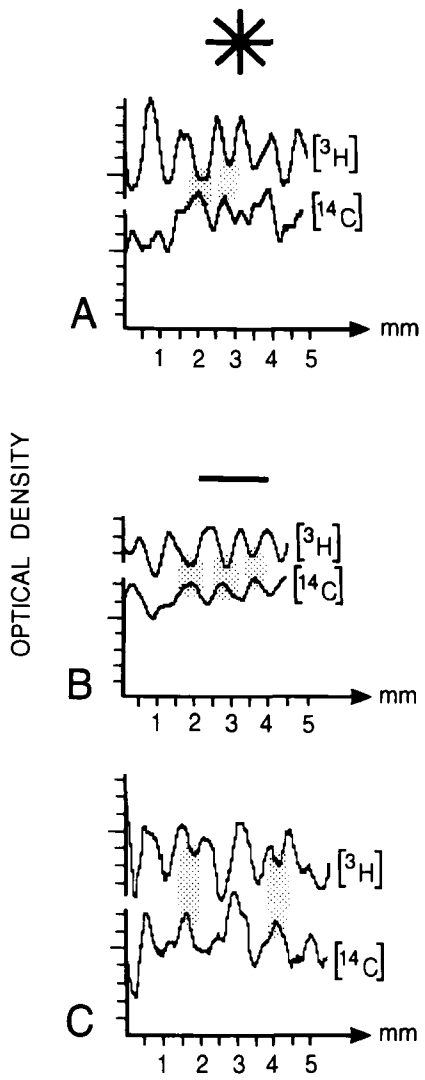


FIG. 5. Optical density distributions measured along identical vectors in corresponding [^{3}H]proline and [^{14}C]2-DG autoradiographs from the left (A) and right (B) visual cortex of cat C1 and the right hemisphere in cat C2. Upper trace: [^{3}H]proline; lower trace: [^{14}C]2-DG. Upward deflections correspond to increased optical densities. The x-axis represents distance on the autoradiographs in mm, the y-axis the optical density in arbitrary units. Note that peaks in [^{14}C]2-DG accumulation can coincide both with peaks and troughs in the [^{3}H]proline pattern (coincidence with troughs: dotted areas).

Superimposition of ^{3}H-labelled ocular dominance columns and ^{14}C-labelled, monocularly induced orientation maps in sections through layer IV again revealed that orientation columns are not exclusively centred over the ocular dominance territories of the stimulated eye (Figs 7 and 8). Regions of increased 2-DG uptake may even be non-overlapping with the ocular dominance domains of the stimulated eye. This is illustrated in Figures 7C and 8C for two different animals: in both cases, the dotted (grey) profiles correspond to regions of increased 2-DG uptake that do not match with thalamo-cortical input. This non-coincident distribution of ^{3}H- and ^{14}C-labelled domains is also visible in optical density measurements along identical vectors in the ^{3}H and the ^{14}C autoradiographs (Fig. 5B and C): there is no consistent topographical relationship between the two patterns.

Since we did not observe any differential labelling in the cortex after monocular stimulation with many different orientations we wondered whether eye-specific activation patterns were resolvable at earlier stages of the visual system. To this end, we analysed the 2-DG patterns in the LGN of the monocularly stimulated animals. In the hemispheres ipsilateral to the open eye, 2-DG uptake is highest in layers A_1 and C_1 (Fig. 9A and E). On the contralateral sides, layers A and C are most heavily labelled (Fig. 9B and D). In two animals, the stimulated eye had also been injected with [^{3}H]proline. Accordingly, the 2-DG 'positive' LGN layers were also ^{3}H-labelled (Fig. 9G and H). To control for the possibility that ^{3}H had contributed to the darkening of the ^{14}C autoradiographs we analysed autoradiographs of the optic

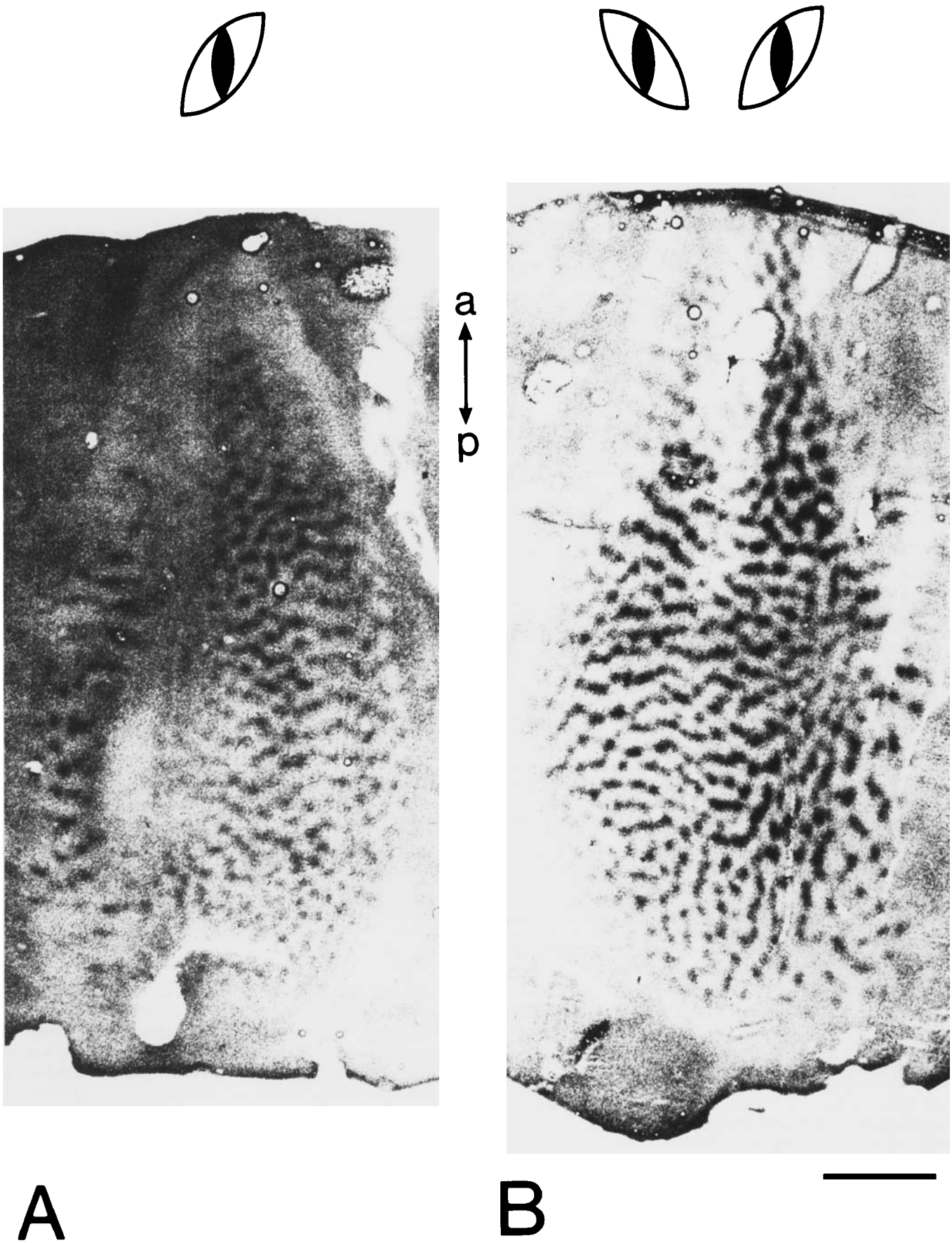


FIG. 6. Patterns of orientation domains induced by monocular (A) and binocular (B) stimulation with moving contours of a single orientation. (A) 2-DG autoradiograph of a flat-mount section of the left visual cortex of cat C3 (ipsilateral to the stimulated eye). Note that a 2–3° wide strip of the visual field bordering the vertical meridian was not stimulated (see Materials and methods). Therefore the cortical representation of this region (the 17/18 border region) is only weakly and homogeneously labelled. (B) 2-DG autoradiograph of a flat-mount section of the right visual cortex of a cat studied in a previous investigation (from Löwel *et al.*, 1987). Abbreviations: a, anterior; p, posterior. Scale bar, 5 mm.

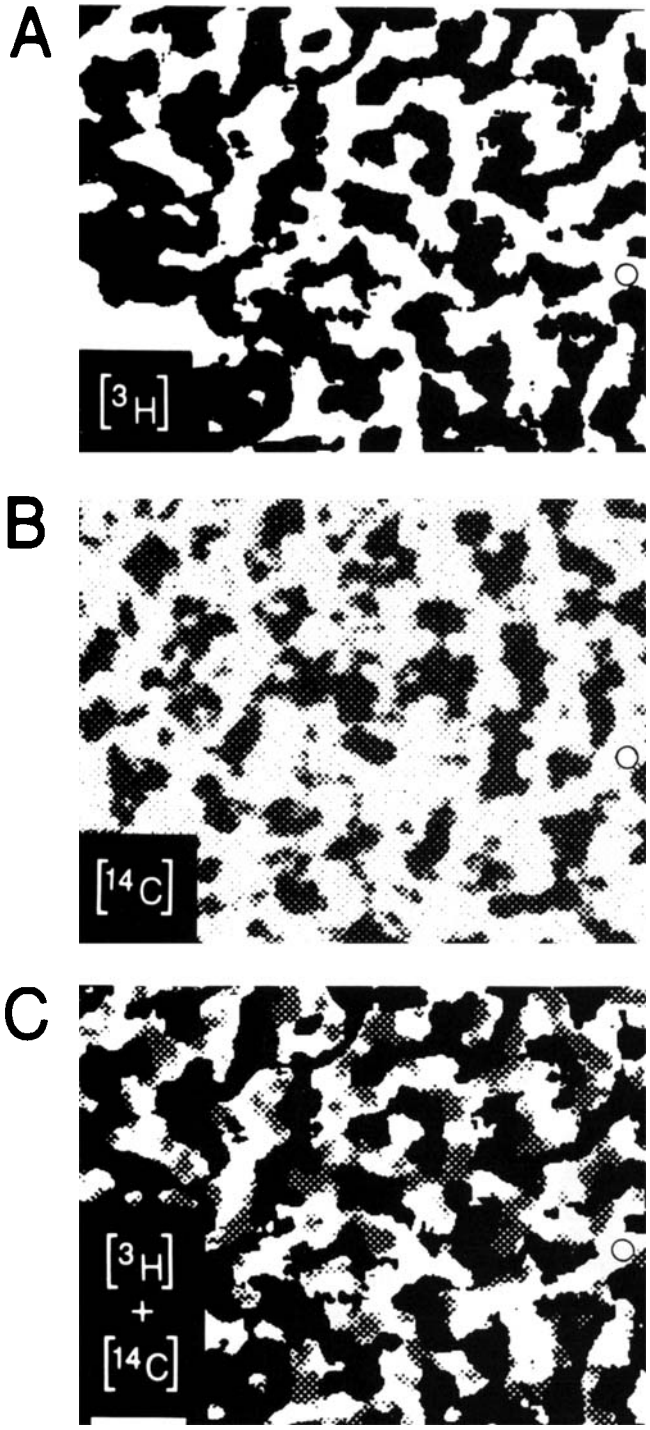


FIG. 7. Contrast-enhanced [^{3}H]proline (A, black profiles) and]^{14}C]2-DG autoradiographs (B, dotted profiles) taken from topographically matched regions of a single section from layer IV of the right visual cortex of cat C1, monocularly stimulated with a single orientation. (C) Superimposition of (A) and (B). Dotted profiles in (C) correspond to regions of increased 2-DG uptake that do not match with thalamo-cortical input. Scale bar, 1 mm.

tract, which is heavily loaded with [^{3}H]proline but should show negligible ^{14}C uptake. This analysis revealed no evidence for ^{3}H contamination of ^{14}C autoradiographs (compare Fig. 9C with F).

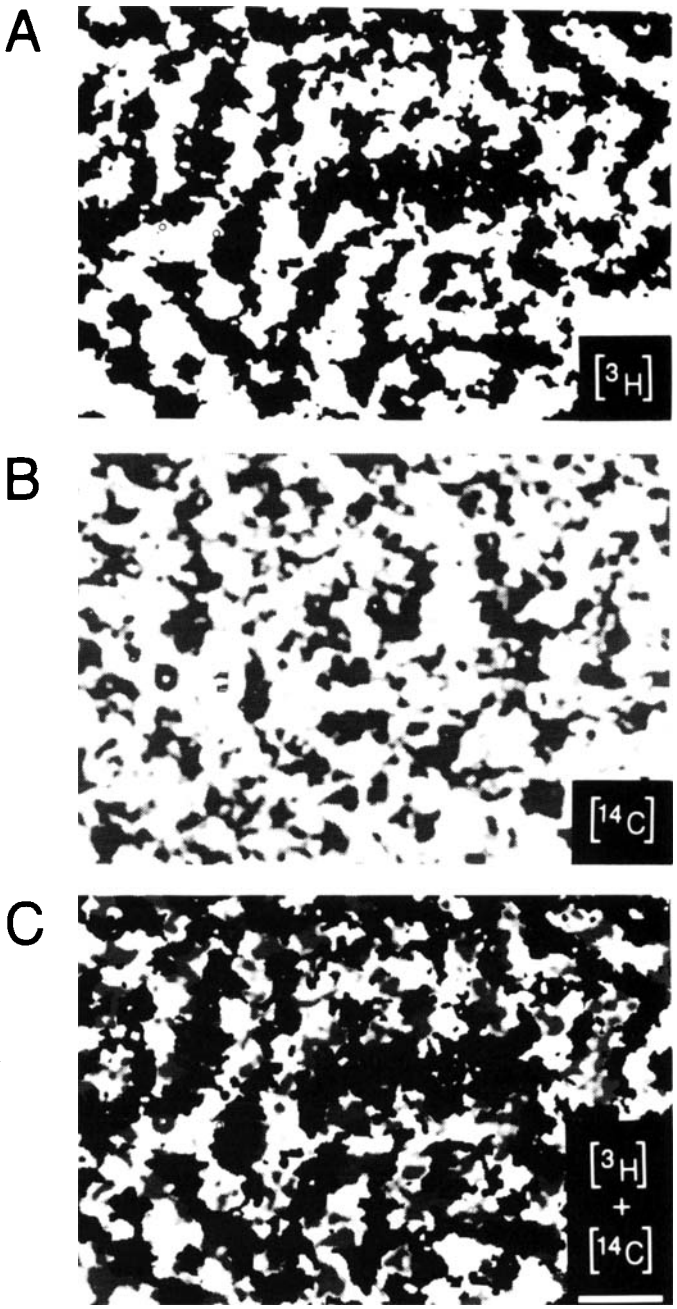


FIG. 8. Contrast-enhanced]^{3}H]proline (A, black profiles) and [^{14}C]2-DG autoradiographs (B, dotted profiles) taken from topographically matched regions of a single section from layer IV of the right visual cortex of cat C2, monocularly stimulated with a single orientation. Note the large oval-shaped and rather homogeneously labelled region in the]^{3}H]proline autoradiograph. It is the cortical representation of the contralateral eye's opic disc. (C) Superimposition of (A) and (B). Dotted profiles in (C) correspond to regions of increased 2-DG uptake which do not match with thalamo-cortical input. Scale bar, 1 mm.

Discussion

The present results indicate that monocular presentation of visual stimuli comprising many different orientations leads to homogeneous activation of striate cortex just as has been described previously for binocular stimulation (Schoppmann and Stryker, 1981; Albus and Sieber, 1984). There was no evidence for reduced 2-DG uptake in territories adjacent

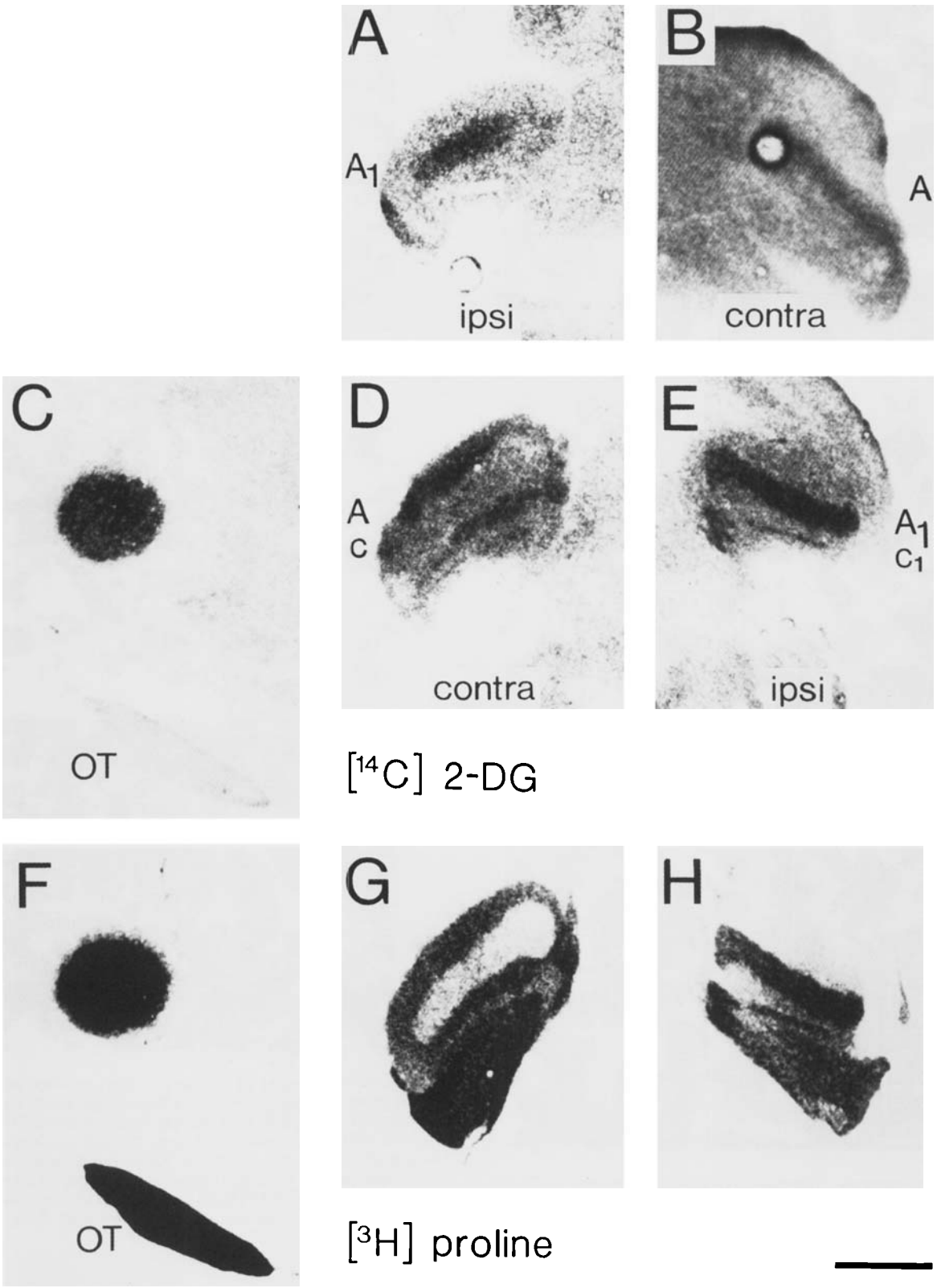


FIG. 9. Patterns of [^{14}C]2-DG and [^{3}H]proline labelling in frontal sections of the LGN of monocularly stimulated cats. (A–E) [^{14}C]2-DG autoradiographs of cats C3 (A, B) and C2 (C, D, E) which were stimulated through the left and right eye, respectively. Ipsilateral to the open eye, 2-DG uptake is highest in layers A_1 and C_1 (A, E). In the contralateral LGN, layers A and C are most heavily labelled (B, D). (F–H) [^{3}H]proline autoradiographs of sections corresponding to the ^{14}C autoradiographs displayed in (C–E). The same LGN layers as in (D) and (E) are labelled (black and dark grey respectively). (C and F) Left LGN (black disc) and optic tract (OT) of cat C2 360 μm anterior of (D) and (E). Note the difference in labelling between ^{3}H and ^{14}C autoradiographs: the OT is labelled on the ^{3}H but not on the [^{14}C]2-DG autoradiographs. Scale bar, 2 mm.

to those receiving direct thalamic input from the stimulated eye. Accordingly, monocular stimulation with only a single orientation produced 2-DG patterns reflecting orientation columns that also did not differ from those obtained previously with binocular stimulation (Albus, 1979; Schoppmann and Stryker, 1981; Singer, 1981; Thompson *et al.*, 1983; Albus and Sieber, 1984; Löwel *et al.*, 1987). Comparison of these orientation maps with the termination sites of the afferents from the stimulated eye revealed that, even within layer IV, activated orientation columns could be completely out of register with the termination sites of the thalamic input responsible for the activation.

Comparison with previous findings

The observation that monocular stimulation with many orientations results in a rather homogeneous accumulation of radioactivity in cat area 17 is in conflict with previous reports of Kossut *et al.* (1983) and Tieman and Tumosa (1983) who found columnar patterns of 2-DG labelling after monocular stimulation and attributed this to ocular dominance columns. One of the cats (C1) of the present study did in fact show slight inhomogeneities of 2-DG uptake after monocular stimulation with many orientations but we interpret these as reflecting orientation rather than ocular dominance domains. First, the spacing of these inhomogeneities corresponded to that of orientation columns (Löwel *et al.*, 1987), and secondly, the inhomogeneities were not related to the ocular dominance columns that were labelled in the same hemisphere with [^{3}H]proline. The inhomogeneities in cat C1 thus most probably correspond to orientation domains and may have resulted from imperfect balancing of stimulus orientation.

This then raises the question why in our experiments monocular stimulation failed to induce measurable differences in 2-DG uptake between activated and non-activated ocular dominance domains. One possibility is that the spatial resolution of our autoradiographic procedure was too low. The ocular dominance domains corresponding to the contralateral eye are less sharply delineated than those of the ipsilateral eye (Shatz and Stryker, 1978; Löwel and Singer, 1987a) and may therefore not have been resolvable. However, the orientation columns in the simultaneously processed contralateral hemispheres were very well resolved. Since their spacing is not markedly different from that of ocular dominance columns, the latter, even if of lower contrast, should have been discernible in the contrast-enhanced images.

Another possibility is that our occlusion technique (see Materials and methods) did not sufficiently reduce activity from the closed eye to induce differential labelling between activated and non-activated ocular dominance domains. Tieman and Tumosa (1983) claimed that ocular dominance domains can only be visualized if the spontaneous activity of the retina (Kuffler, 1953) is eliminated by tetrodotoxin injections or by enucleation. Although we cannot exclude this possibility, the marked differences between 2-DG uptake in stimulated and non-stimulated LGN laminae suggest that occlusion has led to differences in activity that are large enough to be resolved with 2-DG labelling.

We believe that the most likely reason for the discrepancy between our results and those of Kossut *et al.* (1983) and Tieman and Tumosa (1983) is that these groups used awake cats. As the results of the accompanying paper show, anaesthesia and paralysis do have profound effects on the activity distributions evoked by monocular stimulation (Löwel and Singer, 1993).

Absence of 2-DG columns after monocular stimulation

It still needs to be resolved, however, why in the present study eye-specific zones of LGN afferents are not labelled differentially—not even in the input layer IV—despite effective monocular stimulation. One reason might be that the fibres from the LGN constitute only a small fraction of all synaptic endings in layer IV. Estimations range from 5–10% using degeneration techniques (Colonnier and Rossignol, 1969; Garey and Powell, 1971) to 28% using electron microscopic autoradiography after injection of [^{3}H]proline into individual LGN laminae (LeVay and Gilbert, 1976). Since the present results indicate that activity is relayed laterally within layer IV from the territories of stimulated LGN afferents to the appropriate orientation columns, it is thus conceivable that the expected modulation of 2-DG accumulation induced by the activated LGN afferents is simply masked by the 2-DG consumption of elements mediating the lateral spread of activity. As a result, 2-DG patterns in cat area 17 seem to be relatively independent of the exact topographical arrangement of incoming thalamo-cortical fibres even in the input layer IV.

An additional reason for the non-resolvability of ocular dominance columns in layer IV is probably the early convergence of afferents from the two eyes onto binocular cells. Because of this, even monocular stimulation activates cortical tissue rather homogeneously. Already in layer IV, most neurons are binocular (Albus, 1975; Shatz and Stryker, 1978) but even the few purely monocular cells are not devoid of input from the non-dominant eye: most cells receive at least inhibitory input from the non-dominant eye (Tsumoto, 1978; Sillito *et al.*, 1980; Kato *et al.*, 1981). Mixing of inputs from the two eyes is even more pronounced in non-granular layers where most of the tangential intracortical connections terminate. It has recently been demonstrated that these intracortical connections link domains of different and the same ocular dominance with equal probability (Matsubara *et al.*, 1987; Gilbert and Wiesel, 1989; Löwel and Singer, 1992). Since 2-DG uptake is caused mainly by synpatic activity—be it excitatory or inhibitory—rather than by discharging neurons (Nudo and Masterton, 1986), extensive lateral synaptic interactions can be expected to contribute significantly to the accumulation of 2-DG.

The maximal distance that needs to be bridged between the termination sites of the thalamic afferents and non-overlapping orientation columns is in the order of 400 μm, the half-width between adjacent ocular dominance columns. Within layer IV, this distance can be spanned by the dendritic arborizations and axon collaterals of the excitatory target cells of the specific thalamic afferents, the spiny stellate cells and pyramidal neurons (Lund *et al.*, 1979). The dendrites of these cells extend radially for at least 100–200 μm and their axon collaterals travel within layer IV for >1000 μm (Lund *et al.*, 1979; Martin and Whitteridge, 1984). Outside layer IV, activity can be relayed laterally over even greater distances by tangential connections which are especially far-reaching in non-granular layers (Fisken *et al.*, 1975; Gilbert and Wiesel, 1979; Rockland and Lund, 1982; Martin and Whitteridge, 1984).

Conclusions

Taken together, these observations suggest that in cat visual cortex (i) there is very early convergence of monocular inputs onto binocular cells which renders monocular and binocular activation patterns similar and (ii) there is substantial lateral spread of activity from thalamic input zones to the different orientation domains already in layer IV which allows for the spatial offset between thalamic input and activated orientation columns.

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Abbreviations

2-DG 2-deoxyglucose
LGN lateral geniculate nucleus

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