Binocular interaction on cells of the dorsal lateral geniculate nucleus of visually deprived cats

Early visual deprivation produces profound abnormalities in the mammalian visual system[9]. In the cat, the period of susceptibility to such deprivation is limited to the second and third postnatal months[8]. In an attempt to find which neural regions were most susceptible to early deprivation, Wiesel and Hubel compared receptive field properties of single visual neurons in visually deprived cats[8,17–19] with those in normal cats[6,7]. Since neurons of the dorsal lateral geniculate nucleus (LGNd) in monocularly deprived (MD) and binocularly deprived (BD) cats had the normal concentric receptive fields, Wiesel and Hubel concluded that early visual deprivation was without great physiological effect on the LGNd[17]. On the other hand, neurons of the striate cortex in MD and BD cats responded abnormally[8,18,19]. They found, in the normal cat, that most cortical units were discharged by appropriate stimuli presented to either eye[7], but that early visual deprivation decreased this binocular interaction. In MD cats, where the effect was more severe, only the non-deprived eye effectively discharged these cortical cells; while in BD cats the binocular interaction was only mildly altered from the normal pattern[8,18,19].

From these experiments, Wiesel and Hubel argued that the geniculostriate synapses are uniquely susceptible to early visual deprivation. They explained the difference between MD cats and BD cats in terms of binocular competition that occurs among these synapses during their development. Since BD rearing provides a binocularly balanced, though impoverished, environment, it results in nearly normal binocular interaction on cortical neurons. However, MD rearing favors the non-deprived eye, allowing that eye to establish dominance over cortical neurons[8,18,19].

This theory of binocular competition during development of the geniculostriate synapses depends upon the LGNd being physiologically unchanged by early visual deprivation, and makes it important to investigate quantitatively the effects of such deprivation on the LGNd. Since a major cortical effect of visual deprivation is an alteration in the normal pattern of binocular interaction on single cells, it may be reasoned that binocular interaction is a sensitive indicator of change in the LGNd caused by deprivation. For most LGNd neurons, receptive fields can be plotted for both eyes[2,12,15]. Although a few such cells can be binocularly discharged, generally the receptive field of one (dominant) eye provides an excitatory input with a concentric organization while that of the other (non-dominant) eye provides an inhibitory input with a non-specific organization. In this study, particular attention was directed to the effect of rearing with eyelid closure upon the inhibitory, binocular interaction on LGNd units of cats, a feature not investigated earlier[17].

Nine kittens at an age of 8–10 days underwent an eyelid closure operation using a previously described suturing technique[8,17–19]. The lid-sutured eyes were then kept closed for 8–12 months. Three of the animals were binocularly sutured (BD cats) and the remaining 6 had right-monocular suture (MD cats). The closed eyes were opened 1–4 weeks prior to single cell recording. Each cat had a strabismus and provided part of the data for a separate study[14].

Single unit extracellular recording with tungsten-in-glass microelectrodes and receptive field analysis closely followed previously described techniques[1,12] and only a brief outline will be given here. Cats were anesthetized (70% N_2O, 30% O_2), paralyzed, artificially respired and placed in a stereotaxic headholder. The receptive fields of LGNd units were handplotted with small flashing spots (0.1°–1.0°) and larger annuli. For quantitative analysis, *average response histograms* were prepared with the aid of a modified RIDL multi-channel analyzer cycled in synchrony with a slit (usually 1° × 8°) moving perpendicular to its long axis across the receptive field; the field of each eye

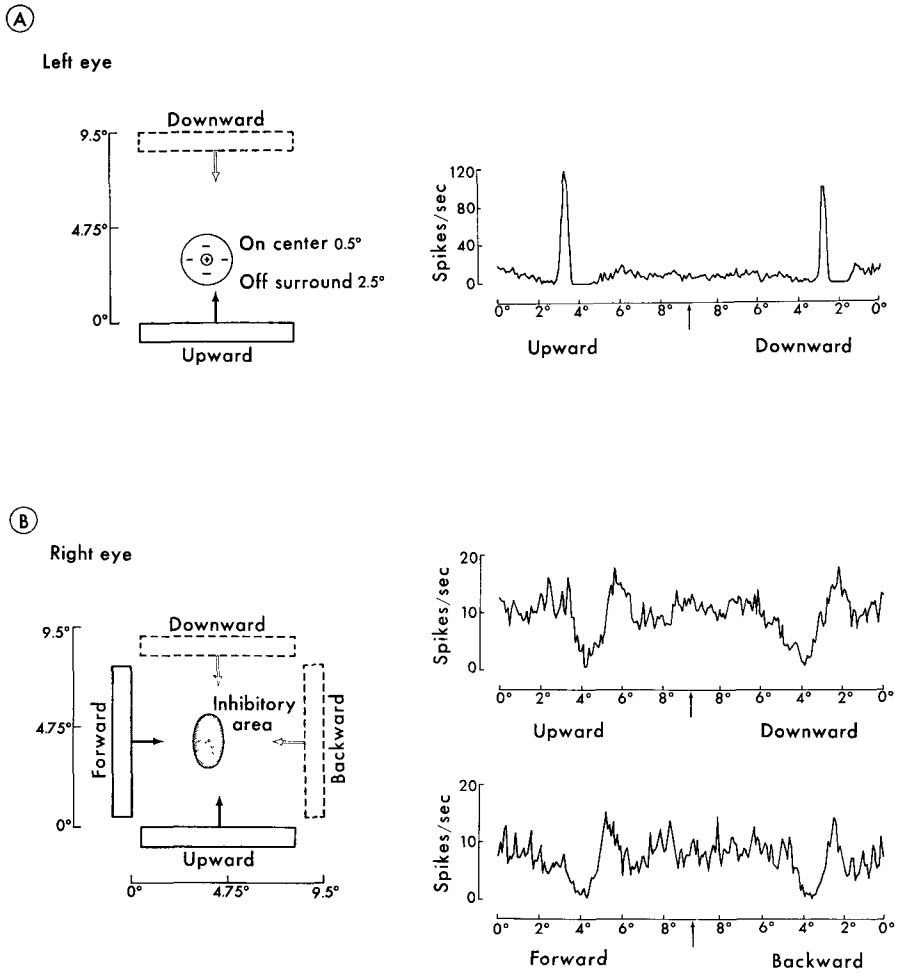

Fig. 1. Typical binocular LGNd unit from lamina A_1 of a BD cat. The left side of the figure represents the movement of the slit (at 9.5°/sec) across the receptive field of each eye; the right side, the average response histograms resulting from the slit movement. The labeling on the slits (forward, upward, etc.) indicates their orientation and direction of movement; and this labeling corresponds to that on the histograms. With the normal spontaneous activity of LGNd units (about 10/sec in this example), both inhibitory and excitatory regions in the receptive field are clearly demonstrated. A, *Dominant (left) eye*: the histogram is typical for a unit with a concentric receptive field organization[10]. B, *Non-dominant (right) eye*: the inhibitory response, with its lack of orientation or direction selectivity, is typical for most units in LGNds of normal cats[12].

was tested independently. The slit had a luminance of about 300 cd/sq.m against a background of about 10 cd/sq.m. The ordinate of each histogram is scaled in spikes/sec, and the abscissa provides a spatial representation of the receptive field. The first (forward or upward) half of each histogram represents stimulus movement in one direction; the second (backward or downward) half, movement in the reverse direction. The abscissa thus plots time consecutively, but the spatial representation reverses along the backward half so that the beginning and end of each histogram represent the same point in object space[1] (see Fig. 1). For the MD cats, equal numbers of separate electrode tracks passed through each pair of LGNds to sample each lamina (A, A_1 and B) whether dominated by the deprived or the normal eye. After the experiment these tracks were reconstructed from histological sections, so that all units in this study could be assigned to one or another of the LGNd laminae.

Receptive fields of all 135 neurons isolated in this study (56 from BD cats, 79 from MD cats) were handplotted and 57 of these (21 BD, 36 MD) were analyzed with average response histograms. All units were within about 17° of the area centralis as determined by previously described methods[13], and were thus within the binocular segment of the visual field. No obvious interlaminar differences were found, so units are grouped in Table I without reference to laminae. ON center, OFF center and ON–OFF center units were encountered as indicated, and with the exception of the units of Fig. 3, had center sizes (0.3°–2°) within the range reported for normal cats[11]. Both ON and OFF center units had antagonistic surrounds. In studies of MD cats, many fewer units were encountered in the 'deprived' laminae (those receiving direct retinal afferents from the deprived eye) than in the 'non-deprived' laminae (those receiving direct retinal afferents from the non-deprived eye), 24 compared to 55 ($P < 0.02$ on a χ^2 test). Since electrodes sampled both LGNds equally in these cats, this apparently represents a true difference in the probability of the electrodes isolating

TABLE I

SUMMARY OF PROPERTIES OF 135 LGNd UNITS POOLED FROM 9 VISUALLY DEPRIVED CATS

Included for comparison are properties of 113 units recorded from normal cats in a previous study[12].

	*Normal cats**	*Non-deprived laminae from MD cats***	*Deprived laminae from MD cats***	*BD cats*
Cell type for dominant eye				
ON center	59	30	17	32
OFF center	53	22	6	21
ON–OFF center	1	3	1	3
Contribution from non-dominant eye				
Excitatory	11	1	0	1
Inhibitory	81	17	9	8
None	21	7	2	12

* Data from Sanderson *et al.*[12].

** The 'non-deprived' laminae are those receiving direct retinal afferents from the non-deprived eye and conversely for the 'deprived' laminae. Thus laminae A and B of the right LGNd and lamina A_1 of the left LGNd are non-deprived for right-eye closure; the remaining laminae are deprived.

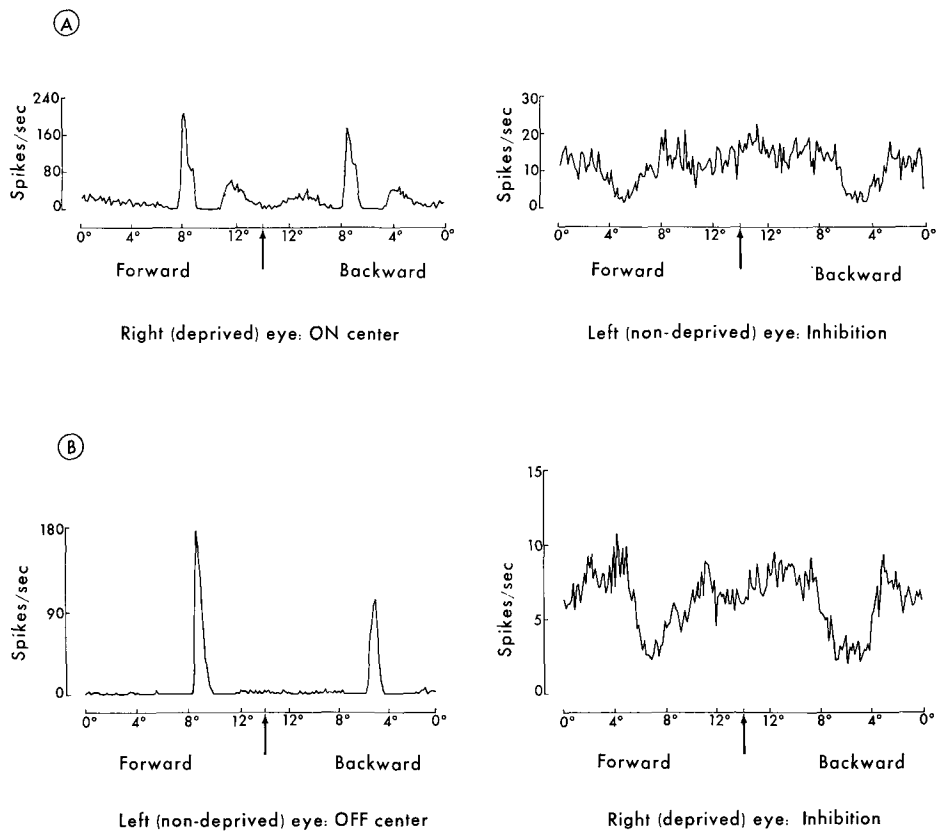

Fig. 2. Typical binocular LGNd units from MD cats, labeling as for Fig. 1. A slit (1° × 8° moving at 14°/sec) was used as the stimulus for each histogram. The dominant responses are typical for units with concentric receptive field organizations[10], and the non-dominant inhibition is typical for normal LGNd units[12]. A, *ON center unit from lamina A*. The dominant eye is the deprived eye. B, *OFF center unit from lamina* A_1. The dominant eye is the non-deprived eye.

units in deprived *versus* non-deprived laminae. Whether this results from *fewer active* neurons in deprived laminae or is a sampling error due to cell shrinkage in these laminae[17], smaller cells being presumably more difficult to isolate, cannot yet be determined.

Table I also indicates that binocular interaction on single cells was still a feature in both the BD and MD LGNds, being present for both ON and OFF center units. Figs. 1–3 illustrate 5 units typical of the binocular cells from these LGNds. Although binocular interaction still occurs on these neurons, a smaller percentage of binocular units were encountered in BD cats as compared to the percentage reported by Sanderson *et al.* for normal cats[12] ($P < 0.001$ on a χ^2 test), or as compared to the MD cats ($P < 0.05$ on a χ^2 test). Although the percentage of MD binocular units is slightly less than the percentage in normal cats, this difference is not statistically significant ($P > 0.20$ on a χ^2 test). Thus binocular interaction on single LGNd cells is significantly reduced in BD cats and reduced only slightly if at all in MD cats. These changes contrast with deprivation changes in the striate cortex where excitatory, binocular

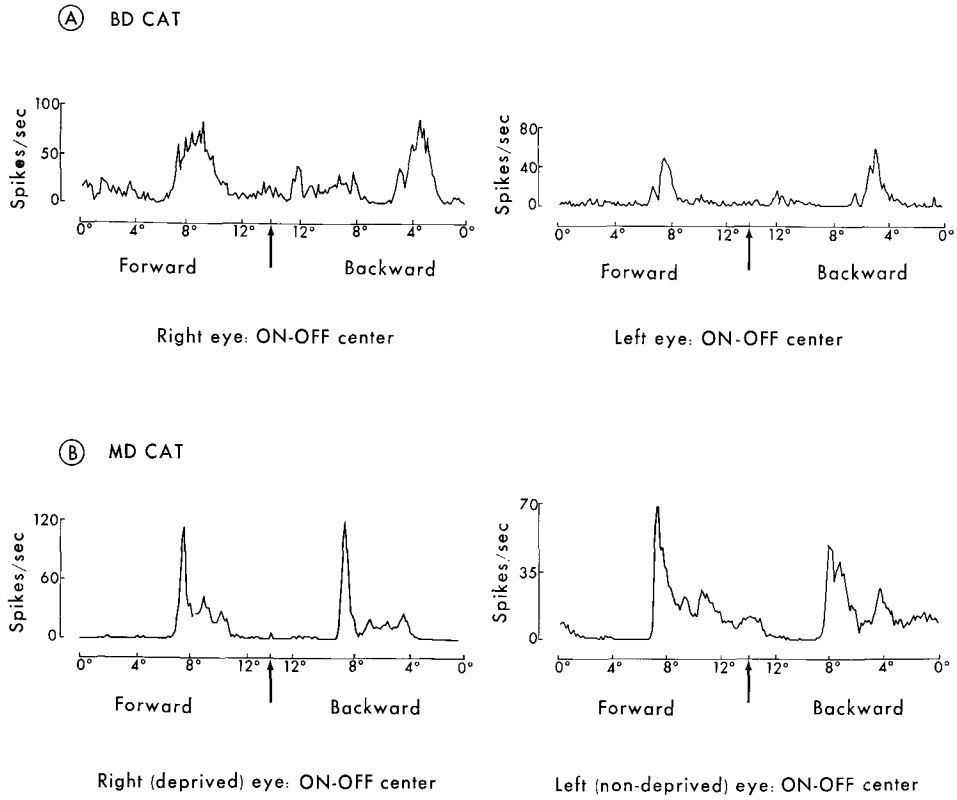

Fig. 3. The two binocularly discharged units found in the LGNds of the visually deprived cats, labeling as for Fig. 1. Both are ON–OFF center units and had larger center sizes (about 4° for the more responsive eye) than any other LGNd unit of this study (see text). Both were probably located in the A–A_1 interlaminar zone, but may have been in either the bottom of lamina A or the top of lamina A_1. A slit (1° × 8° moving at 14°/sec) was used as the stimulus for each of the histograms. A, Binocularly discharged unit from a BD cat. B, Binocularly discharged unit from an MD cat.

interaction on single cells is slightly altered in BD cats and nearly abolished in MD cats[8,18,19]. The concept of binocular competition, formulated to explain the cortical effects of deprivation, seems not to apply to the reduction of inhibitory, binocular interaction on visually deprived LGNd neurons.

Except for the mild reduction in the number of binocular units, this study con firms and extends Wiesel and Hubel's earlier conclusion that LGNd neurons respond normally following early visual deprivation. If these cells are normal, the only other possibility for large deprivation effects peripheral to the striate cortex seems to be a selective disappearance of a functional group of LGNd neurons, while the remaining neurons respond normally. Recent work has demonstrated two separate functional pathways, one involving fast-conducting neurons with phasic responses and the other involving slow-conducting neurons with tonic responses, from retina to striate cortex in the cat[3–5,16]. The functional disappearance of one of these pathways as a result ot deprivation might be related to the apparent reduction of large cells in the deprived LGNd laminae. Whether both pathways are still present after early visual deprivation

is currently under investigation. Until this is resolved, the conclusion that cortical abnormalities due to early visual deprivation 'must be central to the lateral geniculate body'[18] should be held with reservation.

The authors thank Professor P. O. Bishop and Mr. G. H. Henry for advice, Mr. L. Davies and Mrs. J. Campion for technical assistance, and Mrs. M. Heyward for secretarial assistance.

NIH Grant 1 F02 NS4 3310 supported part of this study.

Department of Physiology,
John Curtin School of Medical Research,
Australian National University,
Canberra (Australia)

S. MURRAY SHERMAN*
K. J. SANDERSON**

1 BISHOP, P. O., HENRY, G. H., AND SMITH, C. J., Binocular interaction fields of single units in the cat striate cortex, *J. Physiol. (Lond.)*, 216 (1971) 39–68.
2 BISHOP, P. O., KOZAK, W., LEVICK, W. R., AND VAKKUR, G. J., The determination of the projection of the visual field on to the lateral geniculate nucleus of the cat, *J. Physiol. (Lond.)*, 163 (1962) 503–539.
3 CLELAND, B. G., DUBIN, M. W., AND LEVICK, W. R., Sustained and transient neurones in the cat's retina and lateral geniculate nucleus, *J. Physiol. (Lond.)*, 217 (1971) 473–496.
4 FUKADA, Y., Receptive field organization of cat optic nerve fibers with special reference to conduction velocity, *Vision Res.*, 11 (1971) 209–226.
5 HOFFMANN, K.-P., AND STONE, J., Conduction velocity of afferents to cat visual cortex: a correlation with cortical receptive field properties, *Brain Research*, 32 (1971) 460–466.
6 HUBEL, D. H., AND WIESEL, T. N., Integrative action in the cat's lateral geniculate body, *J. Physiol. (Lond.)*, 155 (1961) 383–398.
7 HUBEL, D. H., AND WIESEL, T. N., Receptive fields, binocular interaction and functional architecture in the cat's visual cortex, *J. Physiol. (Lond.)*, 160 (1962) 106–154.
8 HUBEL, D. H., AND WIESEL, T. N., The period of susceptibility to the physiological effects of unilateral eye closure in kittens, *J. Physiol. (Lond.)*, 206 (1970) 419–436.
9 REISEN, A. H., Sensory deprivation, *Progr. Physiol. Psychol.*, 1 (1966) 117–147.
10 RODIECK, R. W., Quantitative analysis of cat retinal ganglion cell responses to visual stimuli, *Vision Res.*, 5 (1965) 583–601.
11 SANDERSON, K. J., Visual field projection columns and magnification factors in the lateral geniculate nucleus of the cat, *Exp. Brain Res.*, 13 (1971) 159–177.
12 SANDERSON, K. J., BISHOP, P. O., AND DARIAN-SMITH, I., The properties of the binocular receptive fields of lateral geniculate neurons, *Exp. Brain Res.*, 13 (1971) 178–207.
13 SANDERSON, K. J., AND SHERMAN, S. M., Nasotemporal overlap in visual field projected to lateral geniculate nucleus in the cat, *J. Neurophysiol.*, 34 (1971) 453–466.
14 SHERMAN, S. M., Development of interocular alignment in cats, *Brain Research*, 37 (1972) in press.
15 SINGER, W., Inhibitory binocular interaction in the lateral geniculate body of the cat, *Brain Research*, 18 (1970) 165–170.
16 STONE, J., AND HOFFMANN, K.-P., Conduction velocity as a parameter in the organization of the afferent relay in the cat's lateral geniculate nucleus, *Brain Research*, 32 (1971) 454–459.
17 WIESEL, T. N., AND HUBEL, D. H., Effects of visual deprivation on morphology and physiology of cells in the cat's lateral geniculate body, *J. Neurophysiol.*, 26 (1963) 978–993.
18 WIESEL, T. N., AND HUBEL, D. H., Single cell responses in striate cortex of kittens deprived of vision in one eye, *J. Neurophysiol.*, 26 (1963) 1003–1017.
19 WIESEL, T. N., AND HUBEL, D. H., Comparison of the effect of unilateral and bilateral eye closure on cortical unit responses in kittens, *J. Neurophysiol.*, 28 (1965) 1029–1040.

* Present address: Department of Anatomy, School of Medicine, University of Pennsylvania, Philadelphia, Pa. 19104, U.S.A.
** Present address: Department of Anatomy, Bardeen Medical Laboratories, University of Wisconsin, Madison, Wisc. 53706, U.S.A.