J. Physiol. (1976), **255**, *pp.* 299–320
With 9 text-figures
Printed in Great Britain

LATERAL GENICULATE RELAY OF SLOWLY CONDUCTING RETINAL AFFERENTS TO CAT VISUAL CORTEX

BY B. G. CLELAND, W. R. LEVICK, R. MORSTYN AND H. G. WAGNER*

*From the Department of Physiology, Australian National University Canberra, Australia and *the National Institute of Neurological and Communicative Disorders and Stroke, Bethesda, Maryland, U.S.A.*

(*Received 6 August 1975*)

SUMMARY

1. Lateral geniculate neurones of the cat were studied in terms of the latency for activation by local electrical stimulation of the retina, the latency of electrical activation from the visual cortex and properties of receptive fields. Most of the units were relay cells (antidromic activation from visual cortex) but a small proportion were trans-synaptically activated from the cortex. The latter group included units with on–off, on-centre or off-centre receptive fields.

2. Direct activation of lateral geniculate neurones from local electrical stimulation of retinal ganglion cells or their axons in the retina was identified by the sharpness of timing of the elicited impulses. This procedure revealed the existence of slowly conducting axons relaying in the lateral geniculate nucleus.

3. The distribution of latencies for direct activation from the retina was bimodal with an extended tail of long values. It is similar to the distribution of antidromic latencies of retinal ganglion cells following stimulation of the optic tract.

4. There was a tendency for geniculate neurones with fast input from the retina to have fast axons to the visual cortex and correspondingly for medium-speed and slow input.

5. The previous classification of geniculate receptive fields into sustained and transient types was extended to include commonly encountered 'brisk' and uncommonly encountered 'sluggish' varieties of each. The extension was based on visual properties and latency for direct electrical activation from the retina. Units with receptive fields differing from the familiar on-centre or off-centre concentric pattern were encountered rarely; they included colour-coded fields, local-edge-detectors and one edge-inhibitory off-centre type.

6. There was differential distribution of cells by layer according to receptive field type. It principally involved a paucity of brisk-sustained cells and a relative preponderance of sluggish-sustained, sluggish-transient and non-concentric types in the C layers.

INTRODUCTION

Commonly encountered neurones of the cat's lateral geniculate nucleus (LGN) possess concentrically organized receptive fields of the on-centre off-surround or off-centre on-surround type (Hubel & Wiesel, 1961). These have been further subdivided into sustained and transient classes (Cleland, Dubin & Levick, 1971*a*). Because of continuing evolution of the classification it is not yet possible to assert a one-to-one correspondence between this subdivision and the tonic/phasic (Fukada & Saito, 1972) or *X*/*Y* (Hoffman, Stone & Sherman, 1972) subdivisions.

Neurones of the transient class were shown to receive direct excitatory input from rapidly conducting optic axons and those of the sustained class from more slowly conducting optic axons (Cleland *et al.* 1971*a*). The fast axons have retino-geniculate conduction times which would place them in the t_1 conduction group of Bishop & McLeod (1954). They originate from ganglion cells of the brisk-transient class (Cleland & Levick, 1974*a*) which have been identified (Cleland, Levick & Wässle, 1975) with the morphologically recognized *alpha* cells in Golgi (Boycott & Wässle, 1974) and cresyl violet preparations (Wässle, Levick & Cleland, 1975).

The more slowly conducting axons corresponded for the most part with the t_2 conduction group of Bishop & McLeod (1954) and they originate from ganglion cells of the brisk-sustained class (Cleland & Levick, 1974*a*) which may be the morphologically recognized *beta* cells of Golgi preparations (Boycott & Wässle, 1974).

The identifications established by Cleland *et al.* (1971*a*) were based upon exploration of the retina by a recording electrode in search of the ganglion cell or cells providing the excitatory retinal input to the simultaneously recorded LGN cell. Many of the searches were unsuccessful in the sense that the LGN recording was lost before a ganglion cell was encountered which satisfied the criteria for direct excitatory input. It has since emerged that there exist uncommonly encountered classes of ganglion cells with axons conducting sufficiently slowly in most cases to warrant inclusion in the t_3 conduction group of Bishop, Clare & Landau (1969). Initially, the cells were thought to have receptive fields organized differently from the classical concentric pattern (W-cells: Stone & Hoffman, 1972; Hoffman, 1973), but most of them were soon shown to have the familiar centre-surround organization (Levick & Cleland, 1974).

It was therefore possible that some of the unsuccessful retinal searches were instances of an LGN cell receiving input from uncommonly encountered retinal ganglion cells. In the present experiments the effectiveness of the retinal search procedure was increased by using the retinal electrode for electrical stimulation as well as recording. The expected result, a sharply timed activation of the LGN cell, is not as informative as that available by recording from the ganglion cell supplying the direct excitation, because the visual properties of the ganglion cell are not accessible. Nevertheless, the method can yield a measurement of retinogeniculate latency and thus indirectly indicate which types of ganglion cells supply the LGN.

Preliminary accounts of this work have been published (Cleland, Morstyn, Wagner & Levick, 1975; Levick, Cleland, Wagner & Morstyn, 1975).

METHODS

Experiments were carried out on seventeen adult cats. Anaesthesia was induced with 2–4% halothane in gas mixture ($N_2O:O_2:CO_2$ = 70:28·5:1·5) and continued after surgical procedures with the gas mixture alone. Recordings were made from single units in the right LGN with a stereotaxically positioned tungsten-in-glass electrode (Levick, 1972). A set of stimulating electrodes (tungsten in some experiments, platinum–iridium in others), glass-ensheathed to within 2 mm of the point, were thrust into the visual cortex up to the insulation over the region bounded by coronal planes −3 and +3, parasagittal planes 0 and 2 right (occasionally −4 and +2, 0 and 10 right). The left eye was fixed to a ring encircling the limbus and access to the retina gained through a hollow needle puncturing the coats of the eyeball just in front of the equator.

To provide local electrical stimulation of the retina, a rather coarse version (15–30 μm of exposed sharpened tungsten) of the standard tungsten-in-glass micro-electrode was used. It permitted the recording of unresolved activity of numerous nearby axons and cells in the form of an audible 'swish' on the loudspeaker synchronous with visual stimulation; occasionally, it recorded an isolated unitary potential clear of the unresolved background. The region of visual field where photic stimulation yielded the 'swish' usually formed a thin, arc-like band corresponding to the projection of an arching bundle of optic axons running from more peripheral retina past the electrode tip. The end of the arc closest to the optic disk therefore indicated the position of the electrode relative to the receptive field of a simultaneously recorded LGN cell. The information was used to guide the retinal electrode to the vicinity of the ganglion cells providing the LGN cell's excitatory input.

In some experiments bipolar electrical stimulation was applied at the optic chiasm by means of a shielded pair of sharpened, glass-ensheathed, platinum–iridium wires, the tips of which were 1 mm apart and bared for 1 mm. The resistance between the wires dipped in saline was usually about 20 kΩ, measured with a simple ohm-meter (AVO mark II). The bipole was stereotaxically directed towards the optic chiasm on the right of the mid line. The proper depth was established by monitoring the threshold for the field potential recorded in the LGN to 50 μsec shocks applied as the bipole was lowered. Adjustment was complete when the threshold voltage fell below 1–2 V.

Data processing. Most of the latencies were measured directly with the aid of an oscilloscope (Tektronix 565) displaying the impulses and the stimulus artifact timed to begin exactly 1 msec after the start of the sweep. A 10-turn potentiometer on the oscilloscope determined the timing of a 'delayed trigger out' signal which was employed to add a brief rectangular pip to the displayed amplifier output. This was positioned under visual control to the very beginning of the all-or-none impulses being measured. The latency was immediately determined from the dial reading of the potentiometer. Only occasionally could the S-potential component of the wave form (Bishop, Burke & Davis, 1962*c*) be confidently distinguished from the noisy base line after stimulation; if it was distinct, the latency was measured to its earliest deflexion.

For some of the experiments a suitably programmed computer (Hewlett Packard 2114A) was used to generate peristimulus-time-histograms (PSTHs) of the summed responses to blocks of 100 electrical stimuli delivered at about 1/sec. The nerve impulses were led to a Schmitt trigger with adjustable threshold and the time of occurrence of the Schmitt pulse digitized with a resolution of 10 μsec by a special interface to the computer.

Electrical stimulation of the retina. Pulses of 50 μsec duration and amplitude up to 10 V were coupled through a stimulus isolation unit (Ortec Model 4656). The return circuit was usually completed by a connexion to the eye-ring fastened to the eyeball around the limbus; occasionally the connexion was made to the cannula penetrating the eyeball. Both arrangements gave equivalent results. A capacitance of 0·47 μF was placed in series with the electrode to remove the steady component of current flow. Cathodal (electrode negative) stimuli were generally used since anodal stimulation was observed to lead to more rapid etching of the electrode.

Electrical stimulation of the visual cortex. The purpose was to identify those LGN cells which sent their axons there. A distinction therefore had to be drawn between antidromic activation of the cell and excitatory trans-synaptic activation by a cortico-geniculate efferent fibre or by way of possible excitatory recurrent collaterals of optic radiation axons. Criteria for antidromic activation were based on those of Bishop, Burke & Davis (1962*b*) and Cleland *et al.* (1971*a*). The principal test was the demonstration of a forbidden period after an orthodromic impulse during which an impulse could not be elicited by cortical stimulation, because of collision at some point along the cell's axon. To apply the test, a Schmitt trigger was used to convert each spike potential into a standardized pulse which then triggered in sequence two wave-form generators and one pulse generator (Tektronix). The duration of the first wave-form generator set the maximum recurrence rate of stimuli and the other units provided an adjustable delay from the spike potential to the cortical shock. The forbidden period test does not distinguish between antidromic activation and the special case of an LGN cell receiving its sole excitatory drive from a recurrent collateral branch of the axon of another LGN cell which itself is antidromically activated by cortical stimulation. Supporting criteria are therefore important. The impulses attributed to antidromic invasion were frequently wider and more notched than the orthodromic impulses of the maintained discharge or from visual stimulation, and were never preceded by an S-potential (Bishop *et al.* 1962*b*). Antidromic invasion was also characterized by (i) a steep gradient in the relation between probability of response and cortical stimulus strength, and (ii) relatively little variation of latency with the strength of suprathreshold cortical stimulation. Further details are given in Cleland *et al.* (1971*a*).

Visual stimulation. For technical reasons it was necessary to work with widely dilated pupils and without artificial pupils or correcting lenses. Atropine eye-drops (1%) were applied to paralyse the pupils and accommodation. Eyelids and nictitating membranes were retracted with neosynephrine eye-drops (2·5%). In the

average experiment the horizontal diameter of the pupils would have been in the range 8–12 mm. The properties of receptive fields were assessed by moving hand-held black or white contrast targets over a light or dark frontal tangent screen 172 cm from the eye. The luminance of the light screen was about 12 cd/m^2. Grating patterns (black and white stripes of equal width) of different spatial frequencies were also used. Coloured stimuli were generated by directing a flashlight at the screen with interposed blue (Ilford 622), minus blue (110) or red (204) filters.

RESULTS

Electrical stimulation of the retina

Although stimulation was applied in the layer of ganglion cells and optic nerve fibres, the effects might not be confined to those structures (Doty & Grimm, 1962; Crapper & Noell, 1963). It was therefore necessary to develop criteria for recognizing direct activation of ganglion cells or their axons as distinct from indirect synaptic activation from stimulation of deeper structures. For this purpose recordings were made from single optic tract axons just below the LGN while electrically stimulating at different positions selected by trial in the vicinity of the retinal receptive field.

The threshold for producing a sharply timed activation of an optic tract axon was usually lowest near the centre of the receptive field. A representative set of PSTHs at such a position for various strengths of stimulation is shown in Fig. 1. For stimuli just above threshold extra impulses appeared superimposed upon the evenly spread impulses from the maintained discharge only within a narrow interval (about 0·5 msec) located at a specific time after the stimulus. With stronger stimuli the proportion of successful activations rose abruptly towards 100 % (Fig. 3*A*), the interval containing the extra impulses became slightly narrower and the mean latency shortened slightly. Stronger stimuli also perturbed the even distribution of impulses from the maintained discharge (Fig. 1*A–C*) in different ways depending upon the type of unit, the particular position of the stimulating electrode and the stimulus strength. The perturbations appeared as spread-out periods of increased discharge (multiple impulses) or silent periods which could begin as early as 6 msec after the stimulus and be repeated up to three-times in the first 60 msec. These perturbations could be elicited over a wider range of retinal positions than the sharply timed activation and were graded with stimulus strength over a relatively wide range. The perturbations were taken to represent indirect activation of the ganglion cell by spread of stimulus current to deeper retinal structures whereas the latter were regarded as direct activation of a ganglion cell or its axon. It was occasionally observed with strong cathodal or anodal voltages that the sharply timed activation began to appear as much

as 1 msec earlier than at lower strengths. This was taken to represent activation of the axon at some distance along its length towards the optic disk.

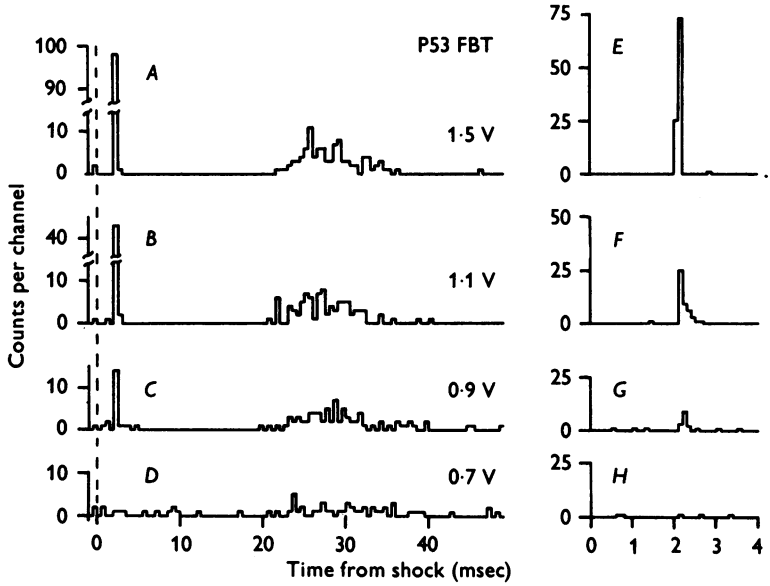

Fig. 1. PSTHs of electrical activation of optic tract axon from the retina. Each row shows (left) slow PSTH (0·5 msec/channel) demonstrating early direct activation and late indirect activation; (right) fast PSTH (0·1 msec/channel) giving expanded display of direct activation. Each PSTH represents the accumulated responses to 100 shocks repeated at about 1/sec. Shock strength (indicated in middle, electrode negative) increases from bottom to top row. Off-centre, brisk-transient receptive field, stimulation near centre.

Electrical activation of LGN cells from the retina

It has been shown (Cleland, Dubin & Levick 1971*b*) that the impulses of an LGN cell have a relatively precise time relation to the impulses in the retinal ganglion cells which provide their excitatory input. It was therefore expected that direct activation of an LGN cell would be recognizable by the occurrence of relatively sharply timed impulses and a narrow peak in the PSTH. These features were readily observed in the case of short-latency activations (Fig. 2*A*). The trial-to-trial variation in timing was rather greater for the LGN cell than for the optic tract axon of similar conduction latency (Fig. 1*E*). When the amplitude of LGN spike-recording was large, the synaptic potential component ('S-potential' of Bishop *et al.* 1962*c*; 'optic-tract synaptic potential' of Hubel & Wiesel, 1961) was sufficiently prominent to be well clear of the noisy base line.

The increased timing variability could then be directly observed to be the result of varying delay from S-potential to the main part of impulse (Bishop, Burke & Davis, 1958). This is illustrated in all three spike records of Fig. 2.

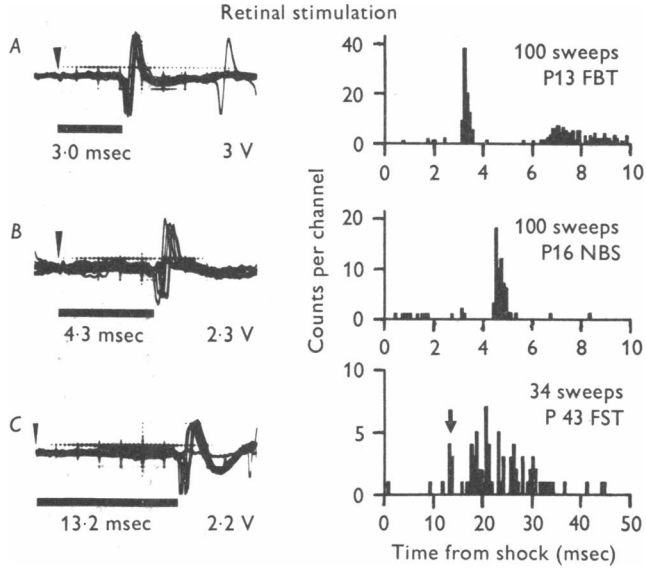

Fig. 2. Electrical activation of LGN cells from the retina. Each row shows (left) superimposed spike records (negative up) with beginning of stimulus artifact indicated by black pointer (shock strength at lower right); (right) PSTHs of summed responses (100 shocks in *A*, *B*; 34 in *C*) on a fast (*A*, *B*: 0·1 msec/channel) or slow (*C*: 0·5 msec/channel) time base. *A*, short-latency (off-centre, 'brisk-transient' type), *B*, medium-latency (on-centre, 'brisk-sustained'), and *C*, long-latency (off-centre, 'sluggish-transient') direct activations (indicated by arrow in *C*).

It was rather more troublesome to find a suitable stimulus position in the case of medium-latency activations (Fig. 2*B*) and the difficulties were usually greatest with the long-latency activations (Fig. 2*C*). The problem was that suprathreshold retinal stimulation elicited a sharply timed impulse on only a proportion of the trials (Fig. 3*C–F*). When the proportion was low (e.g. below 10%) and the latency was long, the observation could be confused by chance occurrence of impulses from the maintained discharge or impulses possibly arising from indirect activation of ganglion cells in the retina (see below). In the example of Fig. 2*C*, a small S-potential was always present at a fixed time near 13 msec whether the main component of the spike occurred or not. This type of observation often helped in detecting those activations attributable to direct stimulation of ganglion cells.

In addition to sharply timed activations, broad waves of increased

discharge were often observed. They resembled corresponding events in the experiments on optic tract axons (Fig. 1*A–C*) in form, timing and dependence upon stimulus position and strength. Such discharge patterns always occurred later (in any given unit) than the sharply timed activations (Fig. 2*A*, *C*) whether the latter were present or not. They were attributed to indirect stimulation of the ganglion cell (or cells) making excitatory synapses with the LGN cell.

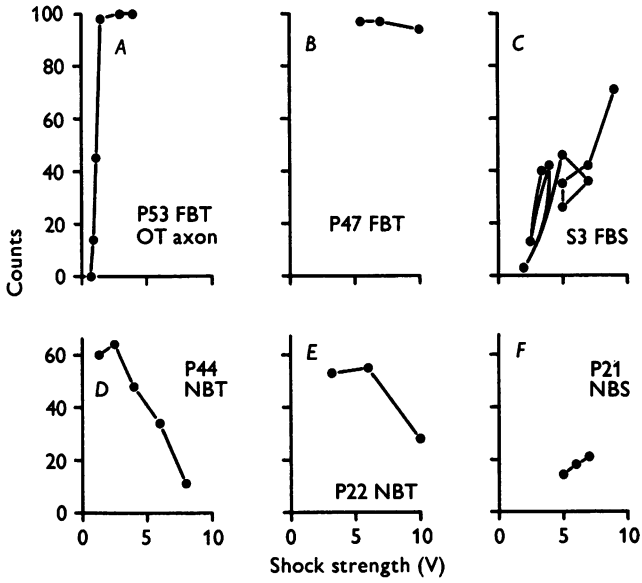

Fig. 3. Representative strength–response relations for direct activation by electrical stimulation of retina. Abscissa, shock strength in volts; ordinate, number of impulses accumulated within direct activation peak (as shown in Figs. 1, 2) after presentation of 100 shocks. *A*, optic tract axon (off-centre, brisk-transient type; same unit as in Fig. 1). *B–F*, LGN cells: *B*, off-centre 'brisk-transient'; *C*, off-centre 'brisk-sustained'; *D*, *E*, on-centre 'brisk-transient'; *F*, on-centre 'brisk-sustained'. In *C*, the points are joined in the order in which they were obtained. There is some uncontrolled non-progressive variation.

Inhibitory effects. Periods of quiescence in the PSTHs were frequently observed when there was sufficient maintained discharge of the LGN cell to provide an evenly spread, noisy base line capable of being suppressed. Such periods were more prominent than in the control experiments on optic tract axons. In particular, suppression could be observed in some cases as early as 3 msec after the stimulus. Periods of quiescence were often apparent at voltages which were subthreshold for the narrow peak of

direct activation. Sometimes, a period of quiescence was the only effect observable at any strength of stimulus.

Another manifestation of apparent inhibitory effects was the observation of a reduction in the proportion of sharply timed activations when stimulus strength was increased. Thus, some stimulus–response curves went through an obvious maximum (Fig. 3*D*, *E*), a feature not yet observed with optic tract axons. Commonly (though not always, Fig. 3*B*), the proportion of activations plotted against stimulus strength remained well short of 100% (Fig. 3*C–F*).

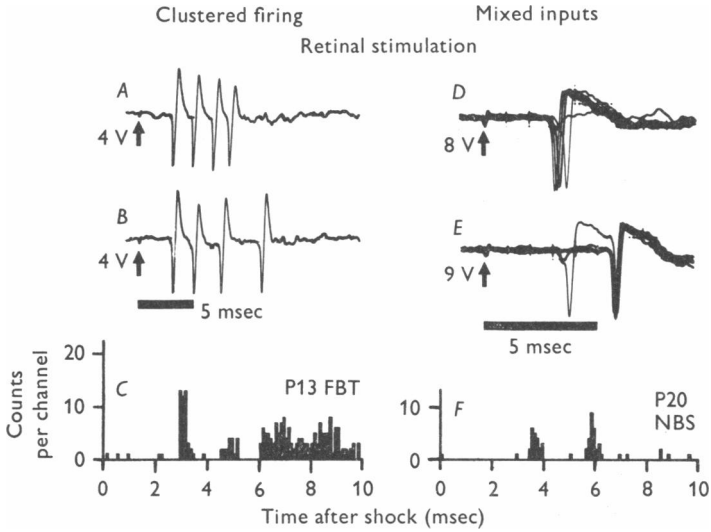

Fig. 4 *A–C*, clustered firing of an LGN cell (off-centre 'brisk-transient') in response to electrical stimulation of the retina. *A*, *B*, spike photographs made a few sec apart to show short-term relative time variation of different spikes in the burst. Beginning of stimulus artifact (4 V shock for both) indicated by arrow. *C*, PSTH for 100 repetitions of the stimulus. *D–F*, duplicate sharply timed activations of an LGN cell (classified as on-centre 'brisk-sustained'). *D*, *E*, superimposed spike records made at different times (slightly different retinal stimulus strength: 8 V in *D*, 9 V in *E*). *F*, PSTH (100 repetitions) under the conditions in *E*.

Clustered firing of LGN cells. At certain times the discharge of LGN cells unpredictably became dominated by infrequent, brief, high-frequency bursts of impulses. This type of behaviour, which has been referred to as 'clustered firing' (Hubel, 1960), was occasionally observed as a response to electrical stimulation of the retina (Fig. 4*A*, *B*). In such a case the first impulse of the burst was sharply timed with respect to the stimulus and produced a narrow peak in the PSTH (Fig. 4*C*). The remaining 1–4 impulses of the burst showed progressively more variation in their individual timing and produced a succession of broader, lower peaks in

the PSTH. A striking feature of the clustered firing response to retinal stimulation was the basically all-or-none behaviour. Although the number of spikes per burst varied from trial to trial, it was not possible to grade the number by varying the stimulus intensity over the available range. When the strength was decreased below threshold for the initial spike the whole burst disappeared.

Mixed inputs. In previous experiments (Cleland *et al.* 1971*a*) it was shown that some LGN cells received direct excitatory input from both transient (fast-conducting) and sustained (more slowly conducting) ganglion cells. Further evidence in support of this was obtained from a few LGN cells in the present series by finding two narrow peaks of activation in the PSTH (Fig. 4*F*) occurring at different times after the stimulus. This situation could be distinguished from repetitive discharge of the LGN cell by noting that the sharply timed impulses of the later peak could occur in the absence of an impulse at the time of the earlier peak (Fig. 4*E*). Fig. 4*D* demonstrates that the prominent S-potential component of the wave form was associated with activation by the short-latency ganglion cell. In other instances, the voltage thresholds for the two peaks were distinctly different and varied relative to each other for different positions of the stimulating electrode.

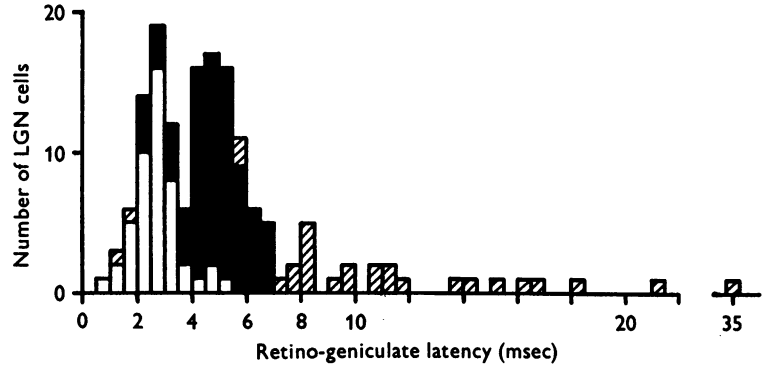

Fig. 5. Histogram of retino-geniculate latencies for direct activation of 158 LGN cells. Open blocks, cells classed as 'brisk-transient'; filled blocks, 'brisk-sustained'; hatched blocks, all other classes.

Retino-geniculate latencies. Attention was restricted to those sharply timed activations of LGN cells which could be elicited at the lowest voltage at the first successful retinal position of the stimulating electrode (near the centre of the receptive field). The latency histogram for 158 cells is shown in Fig. 5. It is double-peaked with a long tail extending to large values of latency. The indicated subdivision of the histogram will be referred to later.

Electrical activation of LGN cells from cortex

In a sample of 357 LGN cells, 250 responded antidromically and a further twenty-two transsynaptically.

Antidromic activation. Representative examples of spike records and PSTHs for activations just beyond the forbidden period are shown in Fig. 6*A–C*. A histogram of the antidromic latencies is shown in Fig. 7. It

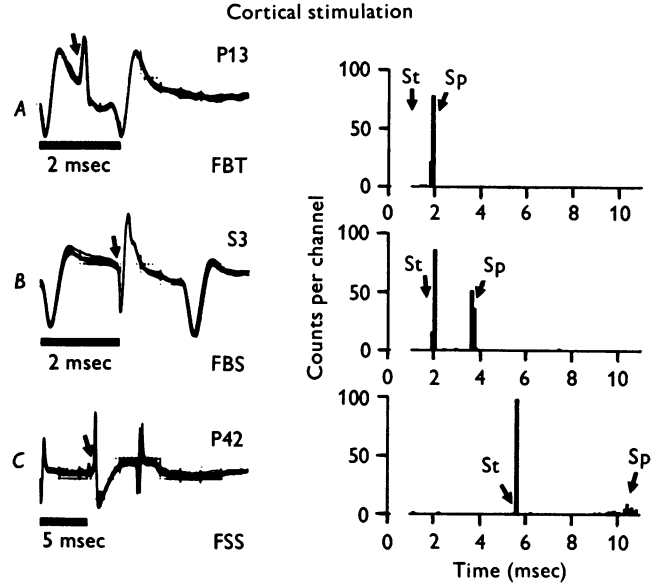

Fig. 6. Antidromic activation from the visual cortex. Each row refers to a different unit: *A*, LGN cell classed as off-centre 'brisk-transient' type (same unit as in Figs. 2*A*, 4*A*, *B*, *C*); *B*, off-centre 'brisk-sustained'; *C*, off-centre 'sluggish-sustained'. In the spike records on the left, each sweep (several photographically superimposed) was triggered by an impulse in the ongoing discharge and the cortical shock (beginning of stimulus artifact indicated by arrow) delivered at the earliest moment at which the response could reliably be obtained. In the corresponding PSTHs on the right (100 repetitions), time begins with the impulse triggering each sweep; the arrow marked 'St' gives the time of the shock (caused triggering of the Schmitt in *B*, *C* and so appeared as an additional peak). The peaks due to antidromic spikes are indicated by 'Sp'.

is monomodal and covers the range 0·3–9·7 msec with a peak about 0·9 msec. The indicated subdivision of the histogram will be mentioned later.

Trans-synaptic activation from cortex. There were twenty-two LGN cells for which a forbidden period for activation could not be demonstrated. The stimulus could be moved arbitrarily close to a preceding orthodromic

impulse without disappearance of the stimulus-evoked impulse (Fig. 8). The activation was therefore by way of transmission across an excitatory synapse on the cell. The cells in this category formed two distinct groups. On the one hand there were eleven which had on-off receptive fields and which were encountered above the level of the first recorded relay cell on that particular penetration. The activations were sharply timed and the latencies ranged from 1–3 msec. The eleven cells of the other group had classical on-centre or off-centre receptive fields and they were encountered

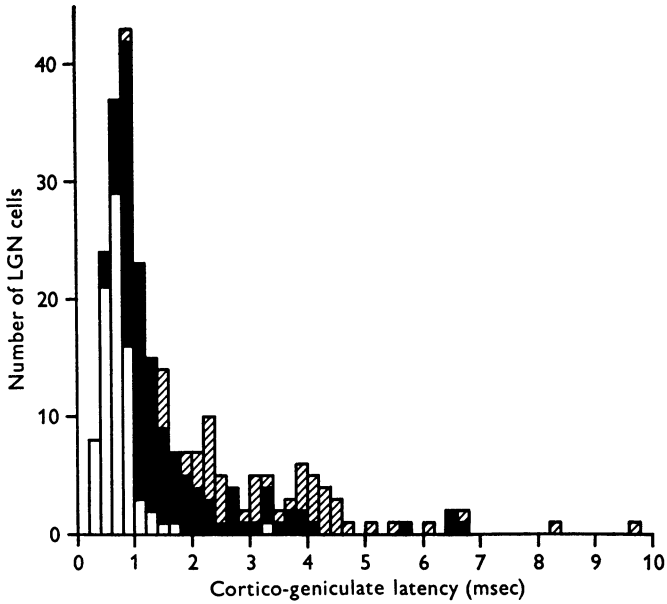

Fig. 7. Histogram of cortico-geniculate latencies for antidromic activation of 250 LGN cells from the visual cortex. Open blocks, cells classed as 'brisk-transient'; filled blocks, 'brisk-sustained'; hatched blocks, all other classes.

within the layers of the LGN (i.e. between the levels of the first-encountered and last-encountered relay cells). The activations were not sharply timed: impulses appeared over a range of several msec beginning in different examples from 4 to 9 msec after the cortical shock (Fig. 8*A*). Increase of shock strength usually led to obvious shortening of latency and multiple spikes (Fig. 8*B*). Most of the units in this group also responded to local electrical stimulation of the retina or optic chiasma (Fig. 8*C*) by giving a rather variably timed impulse. The latency and its range of variation both tended to be longer than would be expected for the type of receptive field of the cell (see later), had it been in the group which showed antidromic activation from the cortex.

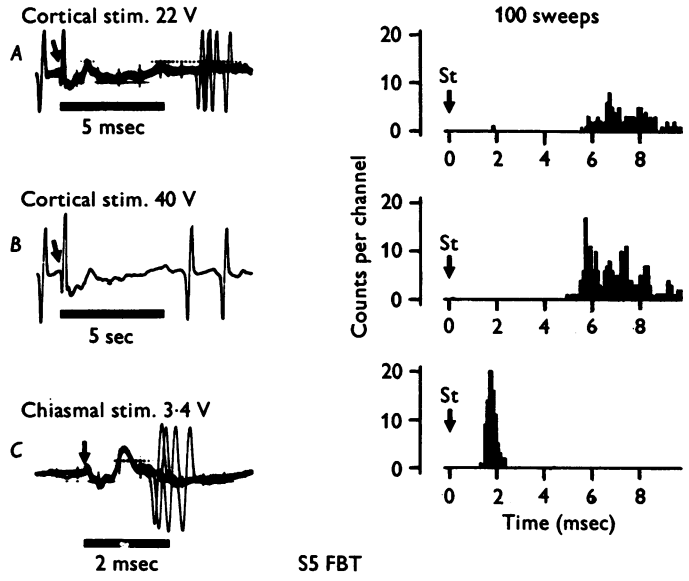

Fig. 8. *A*, *B*, transsynaptic activation of LGN cell (off-centre 'brisk-transient') from stimulation of visual cortex. Spike records (sweeps triggered by impulse from ongoing discharge) on left, corresponding PSTHs (100 repetitions, time reckoned from moment of stimulation, St) on right. *A*, several sweeps photographically superimposed to show substantial latency variation, also shown by PSTH. Note that the stimulus could be moved close (1·2 msec, beginning of artifact indicated by arrow) to a preceding impulse without losing the response. *B*, stronger cortical shock, single sweep photographed to demonstrate two impulses in the response; PSTH shows shortening of mean latency. *C*, activation by stimulation in the optic chiasm. In the spike record (several sweeps superimposed) an arrow indicates the beginning of the stimulus artifact, which is followed by a small complex wave form (LGN field potential). The spike appears with variable latency late on the wave form.

Combined latency measurements

For 115 cells, both retino-geniculate and antidromic cortico-geniculate latencies were obtained. The joint measures are plotted against each other in Fig. 9. In the presence of moderate scatter, short cortico-geniculate latencies tend to be associated with short retino-geniculate latencies and correspondingly for medium and long latencies. The subdivision of the plot by receptive field type will be described in the next section.

Observations on receptive fields

The visual properties were examined in the presence of widely dilated pupils and without artificial pupils or correcting lenses. The behaviour elicited therefore differed from that of a previous report (Cleland *et al.*

1971*a*). In most of the experiments the responses to the finer grating patterns (> 1·5 c/deg) were feeble or absent, the target sizes for which responses were optimum were generally 1·5–2 × larger and the sustained responses of sustained LGN cells were difficult to demonstrate. As reported in previous work (Cleland *et al.* 1971*a*) the irregularity of the maintained discharge of LGN cells and the unpredictable variability in their responsiveness from time to time made it more difficult to draw clear distinctions between different classes of cells than in the retina.

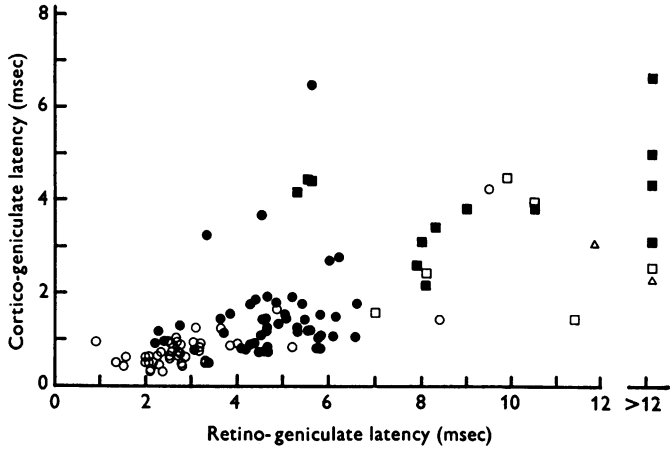

Fig. 9. Scatter diagram of cortico-geniculate latency (antidromic) against retino-geniculate latency for 115 LGN cells. Symbols indicate class of cell: ○ 'brisk-transient'; ● 'brisk-sustained'; □ 'sluggish-transient'; ■ 'sluggish-sustained'; △ 'local-edge-detector'.

Simple testing with manually controlled contrast targets confirmed earlier work (Hubel & Wiesel, 1961; Kozak, Rodieck & Bishop, 1965; Cleland *et al.* 1971*a*) in showing that most of the receptive fields were of the concentric centre-surround type (320 out of 335, after excluding the twenty-two which revealed trans-synaptic activation from visual cortical stimulation). They could also be classed as sustained or transient, but in view of the recent refinement in classification of retinal ganglion cells into commonly occurring brisk and uncommonly occurring sluggish varieties (Cleland & Levick, 1974*a*), it became important to seek evidence for such distinctions in the LGN.

The LGN cells (102) with the closest resemblance to brisk-transient ganglion cells had optimum target sizes of 1·3–3·3°, continued to respond to fast movements (200°/sec) of large targets, responded strongly to rapidly alternated black and white faces of a 2° disk ('twirl' test), gave an essentially transient response to standing contrast and commonly had a demonstrable excitatory periphery effect (McIlwain, 1964; Cleland *et*

al. 1971*a*). Their retino-geniculate and cortico-geniculate conduction times were mostly grouped around the short-latency ends of the respective distributions (open blocks in Figs. 5, 7) and in the lower left region of the scatter diagram (open circles in Fig. 9).

One hundred and sixty-seven LGN cells resembled brisk-sustained ganglion cells: they had small optimum target sizes (0·7–1·3°), gave a modulated discharge to gratings of all effective spatial frequencies and responded feebly to the twirl test. They responded to standing contrast with a sharp leading transient usually followed by a weak sustained discharge. Their retino-geniculate and cortio-geniculate latencies mostly occupied an intermediate range in the respective graphs (filled blocks in Figs. 5, 7; filled circles in Fig. 9).

There were forty units possessing on-centre or off-centre receptive fields which could be classified as sustained (thirty-three) or transient (seven), but which differed from the foregoing in having feeble responses at all times to all forms of visual stimulation. Since the responsiveness of all LGN cells waxed and waned unpredictably, it was necessary to persist with the testing of a feebly responding unit for some 10–15 min to observe that it always remained feebly responsive. Units in this group had optimum target sizes greater than 2°. Their retino-geniculate and cortico-geniculate latencies occupied mostly the long-latency end of the respective ranges. In the scatter diagram (Fig. 9) their points occurred predominantly over the upper right region. The criteria for distinguishing sluggish-sustained from brisk-sustained units was not entirely satisfactory because eleven additional sustained cells had intermediate properties.

Other types of receptive field. Four cells had colour-coded receptive fields like those previously described in the LGN (Daw & Pearlman, 1970; Pearlman & Daw, 1970) and retina (Cleland & Levick, 1974*b*). They responded like vague off-centre units to contrast targets but gave sustained on-responses to projected spots of blue light (Ilford filter 622). Their maintained discharge was reduced by long wave-length stimuli. Three could be antidromically activated from the visual cortex with latencies of 2·2, 3·4 and 4·0 msec.

Six cells responded like the local-edge-detectors in the retina (Cleland & Levick, 1974*b*). They gave a transient burst of spikes when targets either lighter or darker than the background were moved into as well as out of the centre of the receptive field. The target size for optimum responses was 1·3–2°. All five cells could be activated antidromically from the visual cortex. Their cortico-geniculate latencies ranged from 1·58 to 8·3 msec. The retino-geniculate latencies for two were 11·8 and 14 msec; both values are compatible with previous measurements of axonal conduction of retinal local-edge-detectors (Cleland & Levick, 1974*b*).

One cell behaved like the edge-inhibitory off-centre type of retinal ganglion cell (Cleland & Levick, 1974*b*). It had an irregular maintained discharge varying from 30 to 50 spikes/sec and responded with a sustained increase in firing to a large ($> 3°$) black target moved into the receptive field. Smaller targets, either lighter or darker than the background caused reduction of discharge. The retino-geniculate latency was 7·7 msec which is compatible with the (very small) sample of measured conduction times of the corresponding type of unit in the retina.

Four cells could not be classified though they were vaguely visually responsive.

In the remainder of this paper, the particular classes of LGN cells described above will be called by the name of the class of retinal ganglion cell which they most closely resembled. This is for convenient reference only and should not be taken to imply anything more than resemblance at the present stage.

Laminar distribution. Cells having different types of receptive fields did not appear to be evenly distributed between the various layers of the LGN (Table 1). Whereas brisk-sustained cells were found in layers A and A_1, they were very poorly represented in layers C and C_1. Brisk-transient cells occurred in layers A, A_1 and C but not in C_1. Sluggish-sustained were uncommonly encountered in A and A_1 but made up a substantial proportion of the recordings in C and C_1. The remaining types were observed only in C or C_1. The sample included only six cells in C_1.

DISCUSSION

Retino-geniculate latency

Electrical stimulation in the retina rather than in optic nerve or tract has both advantages and disadvantages. The advantages are (i) an effectively longer conduction path (by virtue of the non-myelinated intraocular segment of the axons) to provide the best separation of conduction groups; (ii) the possibility of highly localized stimulation, to favour the appearance of slowly conducted excitation in the LGN by minimizing the potent, early inhibition following synchronous activation of large numbers of optic axons (Suzuki & Kato, 1966; Kato, Yamamoto & Nakahama, 1971). The principal disadvantage is the possibility of indirect activation rather than direct stimulation of ganglion cells or their axons because of stimulus spread to deeper retinal structures. Thus a measured latency might not correspond with the conduction time from ganglion cell to LGN cell. This confusion was avoided by observing the behaviour of the response: direct stimulation of ganglion cells or their axons was associated with a sharply timed impulse in LGN cells, just as in optic tract axons.

TABLE 1. Laminar distribution of 335 LGN cells

Type of unit	LGN layer: A No.	A %	A_1 No.	A_1 %	C No.	C %	C_1 No.	C_1 %	TOTALS No.	TOTALS %
'Brisk-transient'	28	(19·7)	47	(37·9)	27	(42·9)	0	(0)	102	(30·4)
'Brisk-sustained'	103	(72·5)	61	(49·2)	3	(4·8)	0	(0)	167	(49·9)
'Sluggish-transient'	0	(0)	0	(0)	7	(11·1)	0	(0)	7	(2·1)
'Sluggish-sustained'	5	(3·5)	7	(5·6)	19	(30·2)	2	(33·3)	33	(9·9)
Uncertain 'brisk' or 'sluggish'	4	(2·8)	7	(5·6)	0	(0)	0	(0)	11	(3·3)
Colour-coded	0	(0)	0	(0)	2	(3·2)	2	(33·3)	4	(1·2)
'Local-edge-detector'	0	(0)	0	(0)	4	(6·3)	2	(33·3)	6	(1·8)
'Edge-inhibitory off-centre'	0	(0)	0	(0)	1	(1·6)	0	(0)	1	(0·3)
Unclassified	2	(1·4)	2	(1·6)	0	(0)	0	(0)	4	(1·2)
Totals	142	(100·0)	124	(100·0)	63	(100·0)	6	(100·0)	335	(100·0)

The distribution of retino-geniculate latencies is similar to the distribution of antidromic latencies of retinal ganglion cells following electrical stimulation in the optic tract (Levick & Cleland, 1974), if a small allowance is made for added conduction in the present experiments.

The interesting feature in the distribution of retino-geniculate latencies (Fig. 5) is the extended tail of long values (> 7 msec). The equivalent of it appears in the work of Bishop, Burke & Davis (1962*a*: stimulation of optic nerve) and Hayashi, Sumitomo & Iwama (1967: stimulation at optic chiasm), but apparently not in that of Stone & Hoffmann (1971) and Hoffmann *et al.* (1972: stimulation at optic chiasm). The long latencies could arise in two ways. Either (i) the impulse reaches the LGN cell directly (monosynaptically) over a slowly conducting axon, or (ii) the pathway is indirect (polysynaptic) in which case the conduction could be in the fast or medium-speed group. There is some interest in separating these possibilities because one of the unifying features distinguishing the class of slowly conducting W-cells was that their axons went to the midbrain but not to the LGN (Hoffmann, 1973; Fukuda & Stone, 1974).

The evidence, though indirect, favours the first alternative. Firstly, the long-latency activations were relatively sharply timed (Fig. 2*C*). A polysynaptic pathway would have been expected to introduce greater temporal dispersion. Secondly, the receptive fields of the LGN cells with long-latency input resembled those of retinal ganglion cells having slowly conducting axons and differed significantly from those having medium-speed and rapidly conducting axons. The latency of activation was consistent with conduction in the axons of slowly conducting ganglion cells.

Antidromic latencies of LGN cells

The monomodal distribution of values (Fig. 7) is similar to previously published data (Bishop *et al.* 1962*b*; Vastola, 1963; Cleland *et al.* 1971*a*; Stone & Hoffmann, 1971; Fukada & Saito, 1972; Hoffmann *et al.* 1972) but with the addition of a sprinkling of longer latencies. When the histogram is further distinguished according to the receptive field type of the LGN cell obvious heterogeneity appears: 'brisk-transient' cells tend to have faster axons than 'brisk-sustained' cells and these in turn tend to have faster axons than the rest. This reproduces the situation at the retinal ganglion cell level (Levick & Cleland, 1974).

The faster the axon, the larger its calibre. If it is true that the larger the axon calibre, the larger the perikaryal size of the parent cell body, then the various receptive field classes may be the physiological correlate of the dispersion of cell sizes noted in the LGN (Guillery, 1966, 1970). A point in support is that Guillery commented on the prominence of large cells in layer C; units having 'brisk-transient' receptive fields were strongly

represented there (Table 1). A point against is that 'brisk-sustained' units are very much under-represented in layer C, but it is the small cells which are not present there according to Guillery.

It would be premature to push these comparisons, depending as they do on relative encounter frequencies of different physiological types of LGN cells. There is direct evidence from a study on retinal ganglion cells (Cleland *et al.* 1975) that recordings from large cells are substantially over-represented in relation to the anatomical frequency of occurrence. This may also be the case in the LGN.

Mixed inputs to LGN cells

If an LGN cell receives excitatory input from retinal ganglion cells of different functional type, the situation may be described as 'mixed input'. It was observed in earlier experiments (Cleland *et al.* 1971*a*) where the retinal search directly revealed ganglion cells of different types (and having different conduction latencies) providing excitatory input to a simultaneously recorded LGN cell. It occurred in the present experiments as narrow peaks of activation appearing at distinctly different times (Fig. 4*F*) which were separable in terms of stimulus strength and position of retinal electrode. Most cases of mixed input would have been overlooked because the search was not continued beyond the first-encountered activation.

The possibility of mixed inputs may explain some puzzling points on the scatter diagram of Fig. 9. For instance, five cells having 'brisk-sustained' receptive fields appear in the 'brisk-transient' latency-grouping. They may have been cases of mixed inputs; the particular retinal position of the stimulating electrode may have been particularly favourable for the fast-conducting brisk-transient input. Similar suggestions may also account for various other points which appear to be displaced from the main concentration of their particular group.

Interneurones in the LGN

The idea behind separating off the LGN cells which were trans-synaptically activated from the visual cortex was that this group may be candidates for identification with Golgi type-II cells. Detailed accounts of their morphology have been given (Guillery, 1966; Tömböl, 1966/67, 1969). The defining feature is that the axon ramifies entirely within the confines of the LGN, but it is difficult to devise a physiological test that would establish this point. Failure to obtain antidromic activation may simply mean that the stimulating electrodes were not in the proper place. In the rat, I-cells (interneurones) were identified (Burke & Sefton, 1966) by the relatively long repetitive discharge to single optic nerve shocks, by their low threshold but relatively longer latency to optic nerve or cortical

shocks and by the reduction in latency with increasing stimulus strength. In the present experiments the behaviour was rather different. To single-shock stimulation of retina, optic chiasma or visual cortex, no cells manifested long repetitive discharges comparable to those of rat I-cells. The other features mentioned by Burke & Sefton would not be sufficiently decisive in the present situation.

Although the cells in this transsynaptic group differ significantly from antidromically activated relay cells, the present data do not establish them as Golgi type-II cells.

Organizational aspects

Relay cells. The results of this paper indicate the need for a refinement in the earlier classification of the receptive fields of LGN cells. As in the retina the populations of sustained and transient LGN neurones are not homogeneous. A small proportion of each type is distinguished by a feeble responsiveness to optimized visual stimuli, long-latency input from electrical stimulation in the retina and a slowly conducting axon to the visual cortex. It is argued that these are the LGN counterparts of the sluggish-sustained and sluggish-transient types of retinal ganglion cells. With the possible exception of one (or perhaps three) instances (rightmost blocks of histogram in Fig. 8 of Cleland *et al.* 1971*a*) these uncommonly encountered LGN cells were not represented in previous measurements of retino-geniculate latency, presumably because of difficulties in finding the uncommonly encountered ganglion cells which may be their excitatory input. The occurrence of sluggish LGN cells has already been noted by Hubel & Wiesel (1961) in layer B (layers C and C_1 of current terminology) as well as by Kozak *et al.* (1965), where they are referred to under the heading of 'other types' (fourteen in a sample of 130 cells).

For convenient reference the designations 'brisk' and 'sluggish' – previously developed (Cleland & Levick, 1974*a*) for concentrically organized retinal ganglion cells – have been applied to the concentrically organized LGN cells. So there are: commonly encountered brisk-sustained and brisk-transient LGN cells and uncommonly encountered sluggish-sustained and sluggish-transient LGN cells. In addition there are rarely encountered LGN cells lacking the familiar centre-surround organization. They include colour-coded cells, cells resembling the retinal local-edge-detectors and the one cell resembling the retinal edge-inhibitory off-centre type. In the case of the sluggish concentric and non-concentric LGN cells, it cannot be stated with complete certainty that the excitatory inputs come from retinal ganglion cells of the corresponding receptive field type. To be definite about this would require simultaneous recordings of the related retinal ganglion cells so that the visual properties could be checked.

The results establish that there are representatives of all classes of LGN

cells (except the single recorded edge-inhibitory off-centre type) which send their axons to the visual cortex. Some of the classes are recorded from infrequently but they are not necessarily few in number. It may therefore be important to take account of all classes in the attempt to understand the behaviour of cortical neurones in terms of their input.

We are grateful to D. Kirk who helped with a number of the experiments. Miss Erika Beurschgens rendered valuable technical assistance. We appreciated the fine technical contributions of Mr L. M. Davies and staff, and members of the Photographic Unit.

REFERENCES

BISHOP, G. H., CLARE, MARGARET H. & LANDAU, W. M. (1969). Further analysis of fiber groups in the optic tract of the cat. *Expl Neurol.* **24**, 386–399.

BISHOP, P. O., BURKE, W. & DAVIS, R. (1958). Synapse discharge by single fibre in mammalian visual system. *Nature, Lond.* **182**, 728–730.

BISHOP, P. O., BURKE, W. & DAVIS, R. (1962*a*). The identification of single units in central visual pathways. *J. Physiol.* **162**, 409–431.

BISHOP, P. O., BURKE, W. & DAVIS, R. (1962*b*). Single-unit recording from antidromically activated optic radiation neurones. *J. Physiol.* **162**, 432–450.

BISHOP, P. O., BURKE, W. & DAVIS, R. (1962*c*). The interpretation of the extracellular response of single lateral geniculate cells. *J. Physiol.* **162**, 451–472.

BISHOP, P. O. & MCLEOD, J. G. (1954). Nature of potentials associated with synaptic transmission in lateral geniculate of cat. *J. Neurophysiol.* **17**, 387–414.

BOYCOTT, B. B. & WÄSSLE, H. (1974). The morphological types of ganglion cells of the domestic cat's retina. *J. Physiol.* **240**, 397–419.

BURKE, W. & SEFTON, A. J. (1966). Discharge patterns of principal cells and interneurones in lateral geniculate nucleus of rat. *J. Physiol.* **187**, 201–212.

CLELAND, B. G., DUBIN, M. W. & LEVICK, W. R. (1971*a*). Sustained and transient neurones in the cat's retina and lateral geniculate nucleus. *J. Physiol.* **217**, 473–496.

CLELAND, B. G., DUBIN, M. W. & LEVICK, W. R. (1971*b*). Simultaneous recording of input and output of lateral geniculate neurones. *Nature, New Biol.* **231**, 191–192.

CLELAND, B. G. & LEVICK, W. R. (1974*a*). Brisk and sluggish concentrically organized ganglion cells in the cat's retina. *J. Physiol.* **240**, 421–456.

CLELAND, B. G. & LEVICK, W. R. (1974*b*). Properties of rarely encountered types of ganglion cells in the cat's retina and an over-all classification. *J. Physiol.* **240**, 457–492.

CLELAND, B. G., LEVICK, W. R. & WÄSSLE, H. (1975). Physiological identification of a morphological class of cat retinal ganglion cells. *J. Physiol.* **248**, 151–171.

CLELAND, B. G., MORSTYN, R., WAGNER, H. G. & LEVICK, W. R. (1975). Long-latency retinal input to lateral geniculate neurones of the cat. *Brain Res.* **91**, 306–310.

CRAPPER, D. R. & NOELL, W. K. (1963). Retinal excitation and inhibition from direct electrical stimulation. *J. Neurophysiol.* **26**, 924–947.

DAW, N. W. & PEARLMAN, A. L. (1970). Cat colour vision: evidence for more than one cone process. *J. Physiol.* **211**, 125–137.

DOTY, R. W. & GRIMM, FRANCES R. (1962). Cortical responses to local electrical stimulation of retina. *Expl Neurol.* **5**, 319–334.

FUKADA, Y. & SAITO, H. (1972). Phasic and tonic cells in the cat's lateral geniculate nucleus. *Tohoku J. exp. Med.* **106**, 209–210.

FUKUDA, Y. & STONE, J. (1974). Retinal distribution and central projections of Y-, X-, and W-cells of the cat's retina. *J. Neurophysiol.* **37**, 749–772.

GUILLERY, R. W. (1966). A study of Golgi preparations from the dorsal lateral geniculate nucleus of the adult cat. *J. comp. Neurol.* **128**, 21–49.

GUILLERY, R. W. (1970). The laminar distribution of retinal fibres in the dorsal lateral geniculate nucleus of the cat: a new interpretation. *J. comp. Neurol.* **138**, 339–368

HAYASHI, Y., SUMITOMO, I. & IWAMA, K. (1967). Activation of lateral geniculate neurons by electrical stimulation of superior colliculus in cats. *Jap. J. Physiol.* **17**, 638–651.

HOFFMANN, K.-P. (1973). Conduction velocity in pathways from retina to superior colliculus in the cat: a correlation with receptive-field properties. *J. Neurophysiol.* **36**, 409–424.

HOFFMANN, K.-P., STONE, J. & SHERMAN, S. M. (1972). Relay of receptive field properties in dorsal lateral geniculate nucleus of the cat. *J. Neurophysiol.* **35**, 518–531.

HUBEL, D. H. (1960). Single unit activity in lateral geniculate body and optic tract of unrestrained cats. *J. Physiol.* **150**, 91–104.

HUBEL, D. H. & WIESEL, T. N. (1961). Integrative action in the cat's lateral geniculate body. *J. Physiol.* **155**, 385–398.

KATO, H., YAMAMOTO, M. & NAKAHAMA, H. (1971). Intracellular recordings from the lateral geniculate neurones of cats. *Jap. J. Physiol.* **21**, 307–323.

KOZAK, W., RODIECK, R. W. & BISHOP, P. O. (1965). Responses of single units in lateral geniculate nucleus of cat to moving visual patterns. *J. Neurophysiol.* **28**, 19–47.

LEVICK, W. R. (1972). Another tungsten microelectrode. *Med. & biol. Engng* **10**, 510–515.

LEVICK, W. R. & CLELAND, B. G. (1974). Receptive fields of cat retinal ganglion cells having slowly conducting axons. *Brain Res.* **74**, 156–160.

LEVICK, W. R., CLELAND, B. G., WAGNER, H. G. & MORSTYN, R. (1975). Cat lateral geniculate nucleus: long-latency input from retinal ganglion cells. *Proc. Aust. Physiol. Pharmac. Soc.* **6** (in the Press).

MCILWAIN, J. T. (1964). Receptive fields of optic tract axons and lateral geniculate cells: peripheral extent and barbiturate sensitivity. *J. Neurophysiol.* **27**, 1154–1173.

PEARLMAN, A. L. & DAW, N. W. (1970). Opponent color cells in the cat lateral geniculate nucleus. *Science, N.Y.* **167**, 84–86.

STONE, J. & HOFFMANN, K.-P. (1971). Conduction velocity as a parameter in the organization of the afferent relay in the cat's lateral geniculate nucleus. *Brain Res.* **32**, 454–459.

STONE, J. & HOFFMANN, K.-P. (1972). Very slow-conducting ganglion cells in the cat's retina: a major, new functional type? *Brain Res.* **43**, 610–616.

SUZUKI, H. & KATO, E. (1966). Binocular interaction at cat's lateral geniculate body. *J. Neurophysiol.* **29**, 909–920.

TÖMBÖL, THERESE (1966/7). Short neurons and their synaptic relations in the specific thalamic nuclei. *Brain Res.* **3**, 307–326.

TÖMBÖL, THERESE (1969). Two types of short axon (Golgi 2nd) interneurons in the specific thalamic nuclei. *Acta morph. hung.* **17**, 285–297.

VASTOLA, E. F. (1963). Conduction velocities in single fibres of the visual radiation. *Expl Neurol.* **7**, 1-12.

WÄSSLE, H., LEVICK, W. R. & CLELAND, B. G. (1975). The distribution of the *alpha* type of ganglion cells in the cat's retina. *J. comp. Neurol.* **159**, 419–437.