Open Access

Theodore G. Weyand*

The multifunctional lateral geniculate nucleus

Abstract: Providing the critical link between the retina and visual cortex, the well-studied lateral geniculate nucleus (LGN) has stood out as a structure in search of a function exceeding the mundane 'relay'. For many mammals, it is structurally impressive: Exquisite lamination, sophisticated microcircuits, and blending of multiple inputs suggest some fundamental transform. This impression is bolstered by the fact that numerically, the retina accounts for a small fraction of its input. Despite such promise, the extent to which an LGN neuron separates itself from its retinal brethren has proven difficult to appreciate. Here, I argue that whereas retinogeniculate coupling is strong, what occurs in the LGN is judicious pruning of a retinal drive by nonretinal inputs. These nonretinal inputs reshape a receptive field that under the right conditions departs significantly from its retinal drive, even if transiently. I first review design features of the LGN and follow with evidence for 10 putative functions. Only two of these tend to surface in textbooks: parsing retinal axons by eye and functional group and gating by state. Among the remaining putative functions, implementation of the principle of graceful degradation and temporal decorrelation are at least as interesting but much less promoted. The retina solves formidable problems imposed by physics to yield multiple efficient and sensitive representations of the world. The LGN applies context, increasing content, and gates several of these representations. Even if the basic concentric receptive field remains, information transmitted for each LGN spike relative to each retinal spike is measurably increased.

Keywords: LGN; receptive field; retinogeniculate.

Introduction

Anatomical and physiological investigation of the dorsal lateral geniculate nucleus (LGN) has been extensive. It is the LGN that is often promoted as the prototype dorsal thalamic nucleus (e.g. Sherman and Guillery, 2004). The LGN is that thalamic structure that receives from the retina and projects to visual cortex. Because the LGN neurons projecting to cortex are also retinal-recipient, because the retina drives these neurons, and because the receptive field structure of these neurons appears nearly the same as the retinal ganglion cells driving them (concentric), the cells and the structure are tagged 'relay', implying that nothing happens. Given the sophisticated anatomy and exquisite microcircuits, this is a big disappointment. Sherman and Guillery (1996) lament that the thalamus, and the LGN in particular, suffers from 'bad press'. Possibly, but, if the LGN truly has an undeserved image problem, the solution seems not to continue describing its anatomy and microcircuits (e.g. Sherman and Koch, 1986) but to search at a more functional level for operations the LGN engages in that separate it from the retina. Too many past enquiries have sought contrasts between the retina and LGN in paralyzed, anesthetized preparations that did not exploit the statistical properties of the natural environment. Vision is an active process; perception is a conscious process. Vision evolved in a statistically constrained environment; our visual system is tuned to those statistics. These facts all bear on LGN function. After a brief review of design, I describe 10 putative functions associated with the LGN. Collectively, the LGN neuron is well separated from its retinal drive even if the basic concentric receptive field remains. Much of what the LGN does seems to be a judicious 'pruning' of retinogeniculate transmission. Even in the anesthetized animal, this pruning yields an output capable of transmitting ~20–50% more bits/spike of information than its retinal counterpart (Sincich et al., 2009; Uglesich et al., 2009; Rathbun et al., 2010).

Essential design

All LGNs receive a driving input from the retina, and most retinal-recipient neurons are also the same neurons that project to and drive visual cortex (i.e. there is no additional 'middle man' here). In the terminology of Sherman and Guillery (1996), the retinal ganglion cells and the LGN projection cells are both 'drivers'. Retinal innervation has three critical features: (1) it drives LGN neurons, (2) retinal

*Corresponding author: Theodore G. Weyand, Department of Cell Biology and Anatomy, LSU Health Sciences Center, 1901 Perdido Street, New Orleans, LA 70112, USA, e-mail: tweyan@lsuhsc.edu

axons segregate as they enter the LGN by eye and functional group,[1] often forming layers, and (3) retinal axons terminate in discrete, orderly clusters forming the basis for a topographic ('retinotopic') map of the contralateral visual field (with receptive fields similar to retina in size and response properties). Because the retinal ganglion cells drive LGN neurons, and because retinal convergence onto LGN neurons is minimal (often 1:1), it should come as no surprise that the receptive field properties of nearly all LGN neurons seem nearly identical to their retinal drives. Figure 1A shows a trace record from an LGN neuron and its retinal excitatory postsynaptic potential (EPSP) in an awake cat, operating at 50% efficacy (i.e. the LGN ignored the retina half of the time). The bottom part of the figure aligns all EPSPs, indicating that all spikes emerged from that retinal EPSP. The list of agents determining whether a given retinal EPSP will drive an LGN spike is brief, and each is associated with one or more of the functions described below. These include the influence of two extrinsic inputs: a large 'feedback' projection from layer VI of visual cortex (for implementation of graceful degradation, discussed below) and an equally large ascending projection from the brainstem (gating by state, arousal, attention, and eye movements). Figure 2 (left) is a simplified block diagram of the LGN's functional design, whereas Figure 2 (right) is a simplified schematic of the supporting circuitry. The LGN has only two cell types: projection neurons driven by the retina and inhibitory interneurons, which also receive retinal input. The interneurons are supplemented by another class of nearby (extrinsic) inhibitory neurons in the thalamic

reticular nucleus (TRN) that form a local recurrent inhibitory loop in which collaterals of the projection neurons drive TRN cells, which then inhibit LGN relay neurons (recurrent inhibition). Of potential significance is the observation that both the corticogeniculate and brainstem inputs make synaptic contact with LGN projection neurons and interneurons (e.g. Ahlsen et al., 1984; Van Horn et al., 2000). This allows for sign reversal. Second, the types of receptors associated with each brainstem input can also shift, adding intrigue. For example, a brainstem input to a projection neuron can produce an EPSP, whereas axons from that same input can initiate an IPSP on an interneuron (McCormick and Prince, 1987; McCormick and Pape, 1988; Hu et al., 1989a,b; McCormick, 1989). Influence on the relay cell is the same, but via different circuits.

Putative LGN functions

Parsing retinal inputs for selective access by nonretinal inputs

Axons from each eye segregate into zones in the LGN, forming the basis for its distinct laminated appearance. For many species, this parsing segregates not only by eye but also by other attributes, including distinctions between linear/nonlinear summation (X/Y), response vigor (X/Y vs. W), spectral selectivity (magnocellular, parvocellular, and koniocellular), or center polarity (on-center vs. off-center). Schiller and Malpeli (1978) proposed that such 'housekeeping' allowed efficient access of nonretinal inputs to selective populations of retinal groups. This is supported by observations from Sawai and colleagues (1988) in which EEG arousal robustly increased spontaneous and visually evoked activity in the parvocellular C-layers[2] of the cat's LGN, whereas such arousal increased visually evoked but had no influence on spontaneous activity in the A-layers. The interpretation was that brainstem influences differentially affect parvocellular C-layer vs. A-layer cells. This observation is consistent

---

1 Functional group: A principle in sensory system design is division of labor within a modality to specialize for processing particular sensory attributes. For vision, implementation of this division of labor is accomplished by establishing parallel pathways, which begin in the retina and remain largely parallel into the cortex. Each of these parallel pathways would have a private and unique view of the world as they key on particular sensory attributes (differently biased 'snapshots' of the same world). These parallel pathways were originally X- and Y-cells in the cat, distinguished by whether or not the retinal ganglion cell summed luminance across its receptive field (linear, X) or not (Y; Enroth-Cugell and Robson, 1966). Later, a 'W' path was identified based on 'sluggish' response (Cleland and Levick, 1974). The XYW designation has a number of correlates including ganglion cell morphology and axonal conduction velocity. A different designation exists in the monkey: magnocellular, parvocellular, and koniocellular pathways. All of these also have correlates with ganglion cell morphology and axonal conduction velocity. Whereas these three pathways dominate the literature, it is significant that the total number of parallel pathways leaving the retina may actually exceed 15 (cf. Gollisch and Meister, 2010). For a recent review of the 'traditional' magnocellular/parvocellular/koniocellular pathways (which likely accounts for nearly all of the retinal projection to the LGN); see Nassi and Callaway (2009).

2 Layers in the cat's LGN are referenced by the following scheme (from Thuma, 1928; Rioch, 1929; Guillery, 1970; Hickey and Guillery, 1974; Guillery et al., 1980): The A-layers (A and A1) are dorsal, occupy the bulk of the volume, and are nearly all large cell (X and Y); layer A receives from the contralateral eye; A1, the ipsilateral eye. The C-layers have a single large cell contralateral eye layer (C), and three small-cell (parvocellular) layers: C2, C3, and C4. Finally, the cat has a medial division, the medial interlaminar nucleus (MIN) that also receives from the retina and projects to visual cortex. It has three layers designated by Arabic numerals 1, 2, and 3.
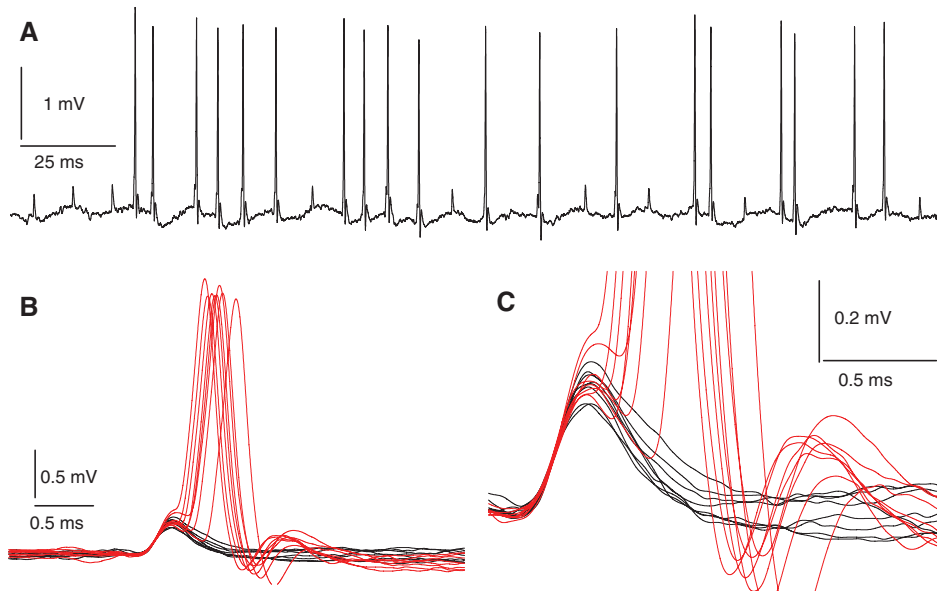
Figure 1: The relay.
(A) Trace from an awake cat showing both LGN action potentials (large events) and retinal EPSPs (small positive events, aka, S-potentials). The retina drives LGN neurons, and these LGN neurons drive visual cortex. This neuron was driven by a single retinal input, a common observation. (B) The first 18 EPSPs have been aligned to show that both 'successes' (EPSPs that generated spikes, indicated in red) and 'failures' (EPSPs that failed to generate spikes) emerge from the same event (amplified in c to show greater detail). Overall, this LGN neuron operated near 50% efficiency (54% over ~1 h). The retinogeniculate synapse is among the most powerful in the brain. The puzzle: What is the benefit of ignoring half of the impulses the retina sends it? (From Weyand, 2007).

with anatomical studies showing different densities and differential targeting of nonretinal axons to different subdivisions within the LGN complex. This includes differences in brainstem targeting (Ahlsen, 1984) and selectivity and density of corticogeniculate axons for specific layers (Robson, 1984; Murphy and Sillito, 1996). Recent results in monkey indicate that corticogeniculate neurons can be segregated by their adherence to magnocellular, parvocellular, and koniocellular properties (Briggs and Usrey, 2009). This physiological observation is consistent with anatomical observations that corticogeniculate neurons can originate in separate sublaminae in layer VI and selectively target, e.g. magnocellular, parvocellular, and koniocellular layers in the LGN (Lund et al., 1975; Conley and Raczkowski, 1990; Fitzpatrick et al., 1994; Ichida and Casagrande, 2002; Ichida et al., 2014).

Comment

Details of morphological features of the LGN fill volumes, and textbooks tend to devote significant space to these details. Speculation on design rationale is scant. Economic packaging is attractive, but as with much of the morphological detail in the brain, we are at a loss to explain why this particular construction is best. The LGN appears to have emerged with vertebrates as the lamprey (a primitive vertebrate) possesses a retinal-recipient nucleus (Kosareva, 1980; Butler, 1994a) that projects into the pallidum and additionally boasts a return projection from that pallidal region (i.e. corticogeniculate; Butler, 1994b, 2008). For reasons that are not clear, it seems vertebrates never invested much real estate in processing at this level of the diencephalon; i.e. the LGN remains compact across all species, retinotopy is the rule, and the retina-recipient neurons are also the cortically projecting neurons. It is understandable that processing capabilities are constrained in the retina; i.e. light must pass through the retinal layers before impinging on rods/cones, so investing in more neurons in the retina would take a toll on optics. It is not clear why investment in processing is so minimal at the level of the LGN; real estate, for whatever reason, must be at a premium. When LGN axons reach visual cortex, expansion is sizeable, pushing 1.5 orders of magnitude (volume ratio V1/LGN; Blasdel and Fitzpatrick, 1984), and things change markedly. A telling observation is that activity in the LGN of a monkey viewing a video of animals at the zoo averages ~20 spikes/s, whereas activity in visual cortex during viewing of the same movies averages <1 spike/2 s (Weyand and Dong, unpublished; but see Vinje and Gallant, 2002). On a more general note regarding LGN design, layering by eye is common, but it
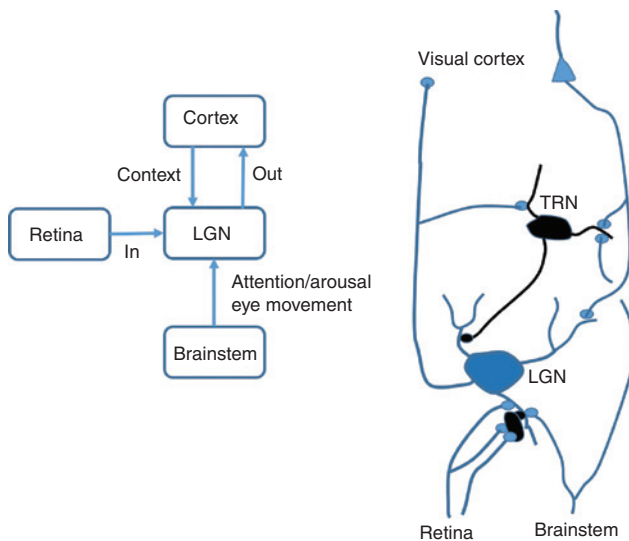
Figure 2: Two schematics of the LGN: flow-chart block diagram emphasizing functional features (left) and basic circuit design (right).

Left: The essential LGN. Sensory input from the retina drives the LGN. Retinal input is necessary but not sufficient. The principal cells that receive from the retina also project to visual cortex. Nonretinal inputs, including local circuits, edit LGN spike output. These include signals regarding state, attention, and arousal from the brainstem, oculomotor signals from the brainstem, and context from visual cortex. Right: Circuit implementation of the functional diagram on the left. Retinal fibers drive the LGN relay cell. Collaterals of the driving retinal axon and other retinal fibers also make contact with an inhibitory interneuron (black blob; in reality, the interneurons have a small soma and extensive dendrites, which rival projection neurons in volume sampled) which then makes contact with the relay cell (feedforward inhibition). The relay neuron projects to and drives neurons in layer IV of visual cortex. As the axon ascends to the cortex, it sends a collateral into the TRN, whose neurons are inhibitory. The TRN neuron then projects back to the LGN relay neuron (recurrent inhibition) or the local interneuron (disinhibition). LGN relay cells are modulated by intrinsic interneurons, TRN neurons, brainstem modulation (inhibitory and excitatory), and a large descending pathway from layer VI. Excitatory influence from layer VI can reverse sign via connections with TRN and intrinsic interneurons. Many details of this circuit are covered in the text.

is sometimes described as hidden (Hayhow et al., 1962); i.e. the layers do not appear to have fiber boundaries. In the rat and rabbit, ipsilateral retinal fibers terminate within a restricted zone with no obvious morphological boundaries. Further, whereas layering typically segregates retinal fibers from each eye, the ipsilateral representation in the rat includes some contralateral retinal fibers, with the result being most neurons in the ipsilateral zone are binocular (Grieve, 2005). With the known exception of the ipsilateral zone in the rat, all other LGN neurons are heavily single-eye dominant; binocular inputs can be demonstrated but are typically indirect and very weak. By

definition, the LGN is retina-recipient. However, the most ventral layers of the cat's LGN (small cell layers referred to as C3 and C4) are not. Apparently, latitude is given to this structure due to its morphological similarity and proximity to other retina-recipient layers immediately dorsal. These small ventral layers receive visual input from the superior colliculus (Harting et al., 1991).

Amplification/integration of retinal signals

Connecting retinal axons to LGN neurons can be a simple one-to-one wiring of excitatory connections but more often involves feedforward inhibition, amplification of signals via multiplexing in which one retinal ganglion cell now drives multiple LGN neurons, and integration in which multiple retinal axons converge on a single LGN neuron. Each of these schemes (illustrated in Figure 3) undermines the 'relay' label. Feedforward inhibition (Figure 3A, e.g. Lindstrom, 1982) refers to the inhibition emerging from retinal collaterals making synaptic contact with inhibitory interneurons. There are two types of feedforward inhibitions based on the origin of the retinal input. In one, a retinal collateral makes synaptic contact with an inhibitory interneuron, which then makes synaptic contact onto an LGN relay cell that also receives a direct excitatory input from the same retinal ganglion cell (e.g. Dubin and Cleland, 1977; Lindstrom, 1982; Mastronarde, 1987b; Blitz and Regehr, 2005; Lindstrom and Wrobel, 2011; Vigeland et al., 2013). In the second, a retinal collateral of one sign makes synaptic contact with an inhibitory interneuron, which then makes synaptic contract with a relay cell of the opposite sign (Mastronarde, 1987b; Wang et al., 2011; Martinez et al., 2014). The former version creates temporal diversity and a type of LGN neuron that does not exist in the retina (the lagged cell; Mastronarde, 1987a,b), whereas the latter enhances the surround and is a form of lateral inhibition. It is important to note that the first form of feedforward inhibition is not exclusive to lagged cells, it is just that this form of inhibition dominates the cell's response (discussed below). Figure 3B shows a situation of simple multiplexing in which collaterals from a single retinal axon innervate and drive multiple LGN principal cells. Such circuitry serves to amplify ganglion cell influence. Figure 3C shows a variation of this theme in which collaterals from several individual retinal ganglion cells multiplex yet then converge on individual LGN neurons (integration). Integration obviously produces receptive fields that do not exist in the retina.

Amplification and integration are significant operations that alter the computational potential of retinal
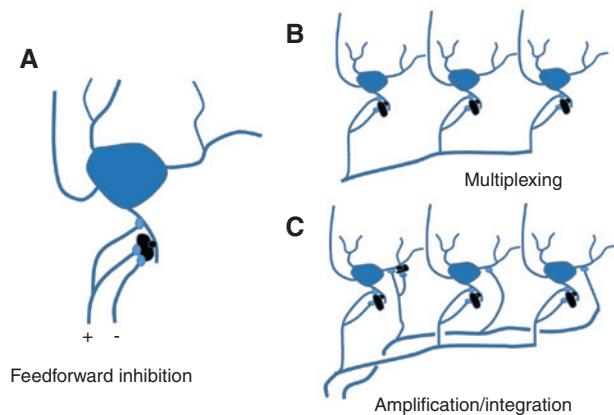
Figure 3: Summary of variations in retinogeniculate wiring. (A) Feedforward inhibition: the retina drives a disynaptic inhibition on relay cells. Retinal fibers make direct contact with proximal dendrites of LGN relay cells. This generates a powerful EPSP driving nearly all LGN spikes. Collaterals of some of these same retinal fibers and axons from retinal ganglion cells of opposite polarity can make contact with dendritic processes of inhibitory interneurons (black blobs), which then make synaptic contact with dendrites on the relay cell. When the source of the retinal input to the inhibitory interneuron is from the same retinal ganglion cell that makes excitatory contact on the LGN neuron, the resulting inhibition is associated with temporal diversity, including construction of lagged cells. When the source of retinal input driving disynaptic inhibition is from retinal ganglion cells of the opposite polarity (e.g. indicated by '–' sign), the circuit could easily enhance the surround (e.g. Martinez et al., 2014). (B) Multiplexing. A given retinal fiber makes synaptic contact with multiple relay cells, providing a means to amplify retinal signals. (C) Integration. Multiple retinal axons converge on LGN neurons, creating receptive fields that do not exist in retina. Multiplexing and integration are often combined.

signals. Even simple multiplexing, in which one generates copies of the same retinal ganglion cell, allows complexities not available at the retina. For one, the strength of the retinal drive can vary, establishing differences in efficacy among LGN elements driven by the same retinal axon. Dynamics of this efficacy could then be tweaked by temporal features of the retinal spike train (discussed below). Second, each of these LGN cells driven by the same retinal ganglion cell could have different local circuit interactions (via feedforward or recurrent inhibition), different intrinsic membrane properties (e.g. altering propensity for 'bursting', activation of a powerful calcium conductance yielding a burst of action potentials; Llinas and Jahnsen, 1982), or different complements of corticogeniculate/brainstem inputs. Any of these, singly or in combination, could alter the propensity for causing the LGN neuron to spike, endowing the circuit with significant computational potential. Because each of these LGN neurons would be driven by the same retinal ganglion cell, synchrony is

likely significant (e.g. Alonso et al., 1996). Presence or absence of the degree of synchrony converging on single cortical neurons would have obvious implications on cortical activity (i.e. temporal summation; Usrey et al., 2000; Alonso et al., 2001; Bruno and Sakmann, 2006; Wang et al., 2010).

Integration of retinal inputs creates receptive fields in the LGN that have no retinal counterpart. Interactions between two LGN neurons receiving multiple retinal inputs with one input shared generates 20% more information when coincident output spikes are treated as a separate channel (Dan et al., 1998). Mastronarde (1992) demonstrated an interesting interaction between two retinal inputs that is nonintuitive and instructive. A Y-cell in layer A was driven by the convergence two retinal Y-cells of the same polarity. Surprisingly, the resulting LGN receptive field was not any larger than either retinal receptive field and the center was located half-way between the receptive field centers of the two retinal inputs. He was able to search the retina to show that the two retinal inputs were neighbors. The LGN receptive field effectively 'filled in' the gap between the two retinal ganglion cell centers. It is not clear how commonly this occurs, nor is the synaptic mechanism known. Nonetheless, it shows a clever way the Y-cell pathway can increase resolution based on common events between overlapping retinal fields. Aspects of integration from nonretinal inputs form the basis for all of the remaining putative LGN functions.

The degree to which retinogeniculate circuits are invested in amplification and integration varies with species and parallel channel. The monkey appears simplest, likely not deviating far from a 1:1 relation between retinal ganglion and LGN neuron. Morphology indicates feedforward inhibitory circuits exist (Wilson, 1989), but amplification and integration of retinal signals appear minimal. A strong indicator that integration of retinal inputs is minimal in the monkey is analyses of S-potentials,[3] the extracellular

---

3 The 'S' or synaptic potential (Bishop et al., 1962) is the retinal EPSP. It is so prominent it can be observed when recording near the cell body using moderately high-impedance microelectrodes. Whereas the EPSP should be extracellular negative, the S-potential is positive. This is most likely because the dendritic sink associated with EPSP produces a sizeable and focused synaptic source at the soma (cf. Bishop et al., 1962). Weyand (2007) did a quantitative analysis showing that for most LGN neurons, S-potential intervals conform to interspike interval distributions observed among retinal ganglion cells. Further, whereas S-potential amplitude can vary twofold among single retinal input neurons (cf. Wang et al., 1985), Weyand (2007) showed that this amplitude variation correlates exactly with events expected from an EPSP; i.e. it is larger when the neuron is expected to be hyperpolarized or if the EPSP interval is long (the retinogeniculate synapse is 'depressing'; Turner and Salt, 1998).

signature of the retinal EPSP (e.g. Figure 1; Bishop et al., 1962; Kaplan and Shapley, 1984; Weyand, 2007). In the monkey, the S-potential is most often attributed to originating from a single retinal ganglion cell. The S-potential receptive field matches the eccentricity and polarity of the simultaneously monitored LGN neuron, its interspike interval distribution matches that of a single retinal ganglion cell, and when S-potentials are observed, the initial slope of nearly all LGN spikes matches the initial slope of the observed S-potential (Lee et al., 1983; Kaplan and Shapley, 1984; Sincich et al., 2007). Interspike interval match is critical; the presence of an S-potential from a second retinal ganglion would yield many intervals <1 ms (cf. Figure 4, Weyand, 2007). Whereas S-potential analysis argues that most LGN neurons are driven by a single retinal ganglion cell, it indicates nothing about the ability of the retinal ganglion cell to drive multiple projection neurons (multiplexing). This too is likely minimal. Michael (1988) recorded from and filled >100 optic tract axons and their terminal arborization into the LGN. None of axons terminated in more than one layer, and the termination patterns were tiny (e.g. 40×100 um) for parvocellular neurons and about double that area for magnocellular neurons. This observation would appear to minimize multiplexing. In addition, to a first approximation, the number of retinal ganglion cells projecting to the LGN matches the number of LGN projection neurons (Schein and de Monasterio, 1987; Spear et al., 1996). Since LGN receptive field sizes closely match their retinal counterpart, this would also minimize integration. Thus, in the monkey, S-potential analysis argues that each LGN neuron is driven by a single retinal ganglion cell and that the size of terminal fields and relative numbers of retinal ganglion cells to LGN neurons are consistent with the assertion that each retinal ganglion cell is driving one and only one LGN relay neuron. Multiplexing is possible but, given the numbers, is likely minimal.

The cat is different. Integration is common, especially among Y-cells. Mastronarde (1992) concluded that ~33% of Y-cells in the A-layers were single input (based on recording from retinogeniculate pairs). Based on cross-correlations of spikes among LGN pairs, Alonso and colleagues (Yeh et al., 2009) reached a number of <10% as being single input. Robson (1993) reconstructed retinal innervation to presumptive Y-cells (Class 1; Guillery, 1966) and observed that it was common for those cells to receive from multiple retinal axons (integration) and for the axons to innervate multiple LGN cells (multiplexing). It is well accepted that LGN Y-cells outside the A-layers receive converging Y-cell input and the receptive fields are much larger than any one of their retinal inputs (Kratz et al., 1978; Dreher and Sefton, 1979; Yeh et al., 2009).

Among X-cells, Mastronarde (1987b) observed that ~80% were driven by a single retinal input. This number aligns well with that of investigators dependent on S-potential records to infer numbers of retinal inputs (e.g. Coenen and Vendrik, 1972; Kaplan and Shapley, 1984; Wang et al., 1985; Weyand, 2007). The degree to which retinal ganglion cells converge on LGN neurons is not without controversy (see Comments, below), but there seems to be reasonable agreement that few Y-cells are driven by a single input, and many, if not most, X-cells are driven by a single input. Multiplexing of retinal input in the cat's LGN is rampant. Compared to the monkey, divergence of retinal axons within layers and across layer is striking (Bowling and Michael, 1980, 1984; Sur et al., 1987). Single Y-axons from the contralateral eye innervate the magnocellular portion of layer C, layer 1 of the MIN, and the A-layers. Amplification of retinal X-cells and especially retinal Y-cells is impressive. Each retina contains 1700 Y-cells; each LGN contains >70,000 Y-cells in the A-layers alone (Peichl and Wassle, 1979). Each retina contains 60,000 X-cells; each LGN, >200,000 (Wassle et al., 1981b; with 90%+ in the A-layers). This yields a >40-fold amplification among Y-cells and a >3-fold amplification among X-cells.

Coverage factor is a term related to amplification of retinal signals and refers to the number of neurons that effectively 'see' a given point in space. It is an integral property of parallel circuits: each pathway should have coverage across the retina, allowing each pathway its own complete 'snapshot' of the world. This snapshot also accommodates overlapping and complementary 'on' and 'off' pathways (i.e. each point is 'seen' by at least one on cell and one off cell). Coverage factor is best documented in the cat. For Y-cells, there is an exquisite lattice that forms for on-center Y-cells and another for off-center Y-cells (Wassle et al., 1981a,b). Even though this arrangement would seemingly yield a coverage factor of 1 for each, physiological mapping places the number closer to 2; i.e. every point in space is seen twice by the on-center Y-cells and twice by the off-center Y-cells (Borghuis et al., 2008). This observation is attributed to extensive dendritic overlap between Y-cells; i.e. close inspection indicates that the lattice is overlapped. As just discussed, for the Y-cells, the >40 amplification observed among Y-cells in the LGN now bumps coverage factor to >80; i.e. any point in space is represented 80 times or more in the cat's LGN. With 60,000 X-cells in each retina, Peichl and Wassle (1979) had a coverage factor of 7–10. As described by Stanley and colleagues (1999), this may be conservative as it references centers only, and they then doubled the estimate (15–20). However, they then underestimate

the ratio of LGN to retina X-cells (1.5, instead of 3) to arrive at an estimate of 20–30 for the LGN. For the X-cells, this estimate is likely conservative.

The cat's LGN appears to be more wedded to amplifying and integrating retinal signals than the monkey, and this is a major difference between the two species. There is much less known regarding retinogeniculate wiring in other species. Conley and colleagues (1987) examined retinal termination patterns in the LGN of the bush baby and tree shrew. Overall, the patterns were restricted to single LGN layers with terminals highly restricted, suggesting minimal convergence and multiplexing. In contrast, in analyzing S-potentials in the rat, I failed to identify a single LGN neuron that received from a single retinal input (0/16, unpublished).

Comments

All retinal ganglion cells do not project to the LGN, presumably reflecting a division of labor among parallel circuits. In the monkey, ~90% of retinal ganglion cells project to the LGN (Perry et al., 1984). This includes magnocellular, parvocellular, and koniocellular retinal axons but, apparently, not all magnocellular and koniocellular neurons. The magnocellular retinal ganglion cells projecting to the superior colliculus do not appear to have collaterals to the LGN (Schiller and Malpeli, 1977). Similarly, Schiller and Malpeli (1977) described a slow-conducting (koniocellular) group of retinal ganglion cells that did not target the LGN. This physiological study seems consistent with HRP studies. Both Michael (1988) and Perry and colleagues (1984) seem emphatic that the axons destined for the LGN were exclusive. In the cat, in which ~75% of retinal ganglion cells project to the LGN (Illing and Wassle, 1981), there seems to be consensus that, certainly, Y-cells branch to innervate both the LGN and superior colliculus, as well as some X-cells innervating both layer A and continuing into the midbrain (Bowling and Michael, 1980; Sur et al., 1987). Whereas there is no direct evidence that retinal W-cells do not branch to innervate both LGN and superior colliculus, morphological analysis suggests that there are two classes of retinal W-cells, with one targeting the LGN and the other targeting the superior colliculus (Stanford, 1987). A suggestive phylogenetic trend is revealed when the rat is considered: only ~28% of retinal ganglion cells project to the LGN (Dreher et al., 1985). The most encephalized species, the monkey, has invested greatly in the retinogeniculate pathway, whereas the least encephalized in this group, the rat, has invested the least.

Consensus regarding retinogeniculate wiring in the cat seems lacking. This is especially pronounced when trying to sort out wiring among the X-cells. Whereas the original retina-LGN paired recordings did not distinguish X- and Y-cells (Cleland et al., 1971; Levick et al., 1972), a figure of 8% of LGN neurons being driven by a single retinal ganglion cell seems low compared to the figure of Mastronarde (1987b; Mastronarde 1992; ~80% of X: ~33% among A-layer Y-cells), who studied retina-LGN pairs and had a large sample. In discussing this discrepancy, Mastronarde (1987b) attributes at least part of this to LGN Ca^{++} bursts in which a single retinal EPSP can trigger a burst (2–5) of spikes (Wang et al., 1985; Wang et al., 2007). Since the underlying biophysics of bursting was not understood at the time, this would have significantly lowered the estimate of LGN cells driven by a single retinal ganglion cell. It is therefore significant that Cleland published a subsequent paper (Cleland and Lee, 1985) studying connected retina-LGN pairs that arrived at a much higher fraction even if the sample was small (12/20 LGN neurons). In an anatomical study requiring herculean effort, Hamos and colleagues (1987) filled an axon from a retinal X-cell and tracked its termination in layer A. Because they could identify both labeled and nonlabeled retinal terminals, they could also determine retinal convergence. The labeled axon innervated four-layer A neurons providing 100% (176/176 of retinal synapses), 49% (21/43), 33% (51/155), and 6% (12/194) of the retinal input of these cells. This clearly showed multiplexing and integration; unfortunately, it was only one axon. Usrey and colleagues (1999) analyzed 12 LGN neurons in the A-layers using a low-impedance electrode array in the LGN and a microelectrode in the retina. Only 1 of the 12 LGN neurons appeared to be dominated by a single input (and they subtracted bursts). It is not clear why their fraction was so low, but the low-impedance LGN electrodes may have introduced a bias. To summarize, monkey LGN cells appear to be driven by a single retinal ganglion cell (assessed by S-potentials and consistency with anatomical observations), LGN Y-cells in cat are most commonly driven by multiple retinal ganglion cells (cross-correlation, anatomical observations), LGN X-cells in cat are most commonly driven by a single retinal ganglion cell (intracellular records, S-potentials; available anatomical data less convincing; cf. Hamos et al., 1987), and LGN cells in the rat are perhaps never driven by a single retinal ganglion cell (Weyand, unpublished). In addition, multiplexing of retinal input in the cat is rampant and would appear minimal in the monkey (based on cell number).

The divergence of retinal Y-cell axons across layers includes projections into the MIN, a structure exclusive to

carnivores. Malpeli and colleagues showed that retinopy in the MIN is largely restricted to the reflective tapetum (Lee et al., 1984), prompting them to suggest that the MIN is specialized for dim-light vision. Follow-up studies showed that MIN Y-cells exhibit a sensitivity advantage of ~0.25 log units (Lee et al., 1992; Kang and Malpeli, 2009) over non-MIN LGN Y-cells. This neural sensitivity aligns well with the cat's behavioral sensitivity (Kang et al., 2009). They argue that the MIN wiring design endows the cat with an advantage at low light levels. Its evolutionary persistence is testament to this advantage and suggests that alternative wiring within the non-MIN LGN to achieve equivalent sensitivity would compromise other visual functions (cf. Lee et al., 1992; Kang and Malpeli, 2009).

Feedforward inhibition is not universal. In the monkey, morphologic analysis indicates inhibitory terminals among magnocellular retinogeniculate synapses, but not parvocellular (Wilson, 1989). This correlates with the observation that the monkey's magnocellular layers contain ~15% interneurons vs. ~4% in parvocellular layers (Hamori et al., 1983; Montero and Zempel, 1986). In the cat, feedforward inhibition is strongly associated with X-cells (by both physiological and anatomical criteria) and, to a lesser degree, Y-cells (anatomical observations; Datskovskaia et al., 2001). In the rabbit, feedforward inhibition in the retinogeniculate circuit appears to be absent (Lo, 1981). As discussed above, feedforward inhibition has two forms: one that contributes to temporal diversity and involves collaterals of the same retinal axon and another that contributes to an enhanced surround and involves collaterals of retinal axons of opposite polarity. This latter form introduces a level of lateral inhibition that does not exist in the retina. Of potential significance in brain design is that at each level beyond the retina, the strength of lateral inhibitory circuits appears to increase, and this increase can be measured by the strength of visual masking at each level (Macknik et al., 2000; Macknik and Martinez-Conde, 2004a,b). Visual masking refers to the diminished visibility of a target achieved by flanking the target with high-contrast stimuli immediately before (forward-masking) or immediately after (backward-masking) target presentation.

Luminance/contrast gain control

Contrast is a measure of the variation in light intensity (luminance) across a local patch of the visual field. In the natural world, even when restricted to photopic conditions, changes in local texture expressed in luminance or contrast can vary by orders of magnitude. To maintain sensitivity, coding for absolute intensity is discarded (although it requires adaptation), and contrast rescales to local conditions. Both of these are implemented by rapidly adapting mechanisms. In free-viewing, we typically shift gaze ~3 times/s, and the changes in luminance and contrast of the images falling on a retinal ganglion (or LGN) receptive field often exceeds an order of magnitude (Mante et al., 2005). Light adaptation occurs mostly in the retina and works to effectively cancel out changes in luminance that occur as the eye shifts from scene to scene. Contrast adaptation begins in the retina and continues into visual cortex. Contrast gain control provides a mechanism by which sensitivity is more evenly distributed across changes in contrast range: maximal at low contrast, minimal at high contrast. This yields a scaled output sensitive to local conditions, not absolutes: an efficient, dynamic design to characterize texture and structure, not levels of brightness. Contrast gain control can be observed in retinogeniculate transmission in which efficacy shifts with contrast (Kaplan et al., 1987; Cheng et al., 1995). Carandini and colleagues (Mante et al., 2008) showed that models incorporating simple RC circuits to mimic both luminance and contrast gain doubled the accuracy of spike prediction in the LGN. Sherman (2004) has suggested that the triadic glomerulus (convergence of retina, interneuron, and brainstem terminal; Szentagothai, 1963; Famiglietti and Peters, 1972) common in the A-layer of the cat is an implementation of a mechanism for contrast gain control. Sherman's (2004) speculation is based on the observation that the glomerulus contains excitatory inputs from the retina, disynaptic inhibition of that retinal input (feedforward inhibition, Figure 3A), and a metabotropic glutamate receptor (mGlu5) that closes a K^+ 'leak' channel, depolarizing the interneuron and increasing its GABA 'drip' onto the relay cell. This receptor is not active at low levels of retinal activity but activates at high levels. As such, the increased inhibition on the relay cell would decrease the gain of retinogeniculate transmission.

Comment

Magnocellular and parvocellular neurons in the retina and LGN differ sharply in contrast gain control. At low contrast, magnocellular neurons are much more sensitive than parvocellular neurons. However, magnocellular neurons begin to saturate for contrasts above ~0.1, whereas parvocellular neurons maintain a linear relation that was still not saturated at 0.64 (highest contrasts used; Kaplan and Shapley, 1986). As discussed above, when viewing natural scenes, significant shifts in luminance

and contrast occur with every saccade, tripping luminance and gain control mechanisms and complicating modeling. When luminance is fixed and contrast is constrained, modeling is greatly simplified. Dan et al. (1996) were spectacularly successful at LGN spike prediction using a simple linear model with mean luminance fixed and contrast confined to a narrow (linear) range. The study by Mante et al. (2008), referenced above, shows that luminance and contrast can be incorporated successfully when luminance/contrast is held within the range associated with viewing natural images.

Though not often discussed, the retina contains luxotonic neurons, i.e. neurons whose output is proportional (or inversely proportional) to light intensity and adapts very slowly, if at all. Whereas earlier studies suggested that these neurons might be restricted to targeting the suprachiasmatic nucleus of the hypothalamus (mediating circadian rhythm) or the pretectum (mediating the pupillary reflex), more recent studies have demonstrated such neurons can target the LGN (certainly in mice; e.g. Brown et al., 2010). Because the extreme sustained nature of these neurons makes them memorable, unless there is some recording bias, it would seem unlikely that such neurons occur in primates and cats with any frequency.

Retinogeniculate gain control by state, level of arousal, and attention

State affects efficacy, the ratio of LGN spikes/retinal spikes. Efficacy increases as state moves from slow-wave sleep to REM-sleep or wakefulness (e.g. Sakakura, 1968; Livingstone and Hubel, 1981; reviewed in McCormick and Bal, 1997). Within wakefulness, efficacy can be further increased by arousal and attention (Swadlow and Weyand, 1985; Sawai et al., 1988; O'Conner et al., 2002; Casagrande et al., 2005; Bezdudnaya et al., 2006; McAlonan et al., 2008). Such gain control is not detectable at the retina (Swadlow and Weyand, 1985). The underlying mechanism seems well documented: changes in activity of the reticular activating system (RAS) depolarize LGN relay cells either directly from brainstem afferents (Singer, 1977; McCormick and Prince, 1987; Hu et al., 1989a,b) or indirectly via inhibition of inhibitory interneurons (McCormick and Pape, 1988).

Comment

Gating by state is well accepted and has been the subject matter of numerous (100s) of investigations, physiological and anatomical. References to state-dependent transmission can be traced to the early 1950s (reviewed in Burke and Cole, 1978), not long after Moruzzi and Magoun's (1949) original description of the RAS. Gating by state and enhanced transmission within state are well accepted. However, there remain several related issues worthy of comment.

Efficacy in wakefulness is often well below 100%

Whereas it is expected that wakefulness improves efficacy over sleep and anesthesia, episodes at 100% efficacy for most cells are brief (<1 s). Reality has efficacy closer to 50%, a striking departure from Coenen and Vendrik's (1972) assertion that wakefulness would normally yield efficacy near 100%. Weyand (2007) observed an overall level of efficacy of 50% in the awake cat, curiously the same level of efficacy observed by Sincich and colleagues (2007) in the anesthetized monkey.[4] There is an irony in the naïve suggestion that efficacy would be 100% in wakefulness: the LGN would become the retina. This does not happen as the LGN is engaged in some sophisticated filtering (the focus of this review) that well exceeds something akin to an 'on-off' switch associated with a sleep/wake dichotomy.

'Spontaneous' activity may not increase with arousal

Whereas activating reticular circuits enhance visually driven activity, the degree to which EEG arousal increases spontaneous LGN activity is not clear. Singer (1977) had proposed that reticular activation (which would cause EEG arousal) would cause a global disinhibition of LGN relay cells, increasing activity. This proposal arose from effects he observed following electrical stimulation of the reticular formation in *encephale isole* cats. This was not observed in awake rabbits. EEG arousal enhanced retinogeniculate transmission during visual stimulation but had no influence on activity with visual stimulation absent (spontaneous activity; Swadlow and Weyand, 1985). The distinction is important as global disinhibition would raise the level of 'noise' in the LGN as well as signal, diminishing the signal-to-noise ratio. If global disinhibition did not raise spontaneous activity, arousal could

---

4 Efficacy may also vary with cell type. Cleland and Lee (1985) showed a Y-cell in layer A that they reported as operating near 100% in the paralyzed, anesthetized cat. Obviously, having that as a common observation would defeat the purpose of having an LGN.

have the effect of raising the signal (enhanced visually driven activity) while leaving noise the same. This conclusion drawn from the awake rabbit was also supported by observations in layer A of the paralyzed, unanesthetized cat, but not in the parvocellular C-layers (Sawai et al., 1988; described above). Whereas it may seem nonintuitive that arousal would selectively enhance visually driven, but not spontaneous, activity (i.e. how would an LGN neuron know the difference?), one explanation might be temporal summation of retinal input. Visual stimulation drives retinal ganglion cells at high firing rates, producing short interspike intervals. Short interspike intervals in retinal ganglion cells are much more likely to drive LGN cells than long intervals (Singer et al., 1972; Mastronarde, 1987b; Usrey et al., 1998; Levine and Cleland, 2001; Rowe and Fischer, 2001; Kara and Reid, 2003; Sincich et al., 2007; Weyand, 2007). Since spontaneous (i.e. no visual stimulation) activity contains (on average) longer retinal interspike intervals, and arousal has no effect on retinal activity (Swadlow and Weyand, 1985), it would be reasonable that arousal would have minimal influence on LGN spontaneous activity.

Long interspike intervals from retina succeed at much higher rates in wakefulness

Despite short retinal interspike intervals being much more successful than long intervals in driving LGN spikes in both wakefulness and anesthesia (above), a major difference in wakefulness is that long intervals can succeed at levels unknown in anesthesia. If 50 ms goes by since the last retinal EPSP, the next retinal EPSP will successfully trigger an LGN spike <2% of the time in anesthesia (e.g. Sincich et al., 2007); in wakefulness, success occurs 13% of the time (Weyand, 2007). In that study, for 9/12 neurons, intervals at 60 ms were successful >10% of the time, with 2 hovering around 40% efficacy. With possible exceptions noted (e.g. a Y-cell; Cleland and Lee, 1985), such efficiency would not occur in anesthesia.

'Bursts' are related to sleep; rare in wakefulness

Early reports (e.g. Hubel, 1960) commented on how LGN activity during slow wave sleep was 'bursty' and relatively steady ('tonic') during wakefulness. McCarley and colleagues (1983) did a quantitative analysis of the burst/tonic behavior among LGN neurons, but only speculated on underlying mechanisms. The combination of Llinas and Johnsen's (1982) discovery of a biophysical basis for

bursting via activation of a calcium channel (t-type) and Crick's (1984) speculative essay triggered an interest in bursts as a special signal in visual processing (reviewed in Sherman, 2001). An interesting property of the t-type channel was that activation required a nominal period of hyperpolarization (called deinactivation) to 'cock the trigger': cause the channel to activate on the next retinal EPSP. T-type calcium channel-mediated bursts are unusual in wakefulness because the membrane potential tends to be depolarized (Hirsch et al., 1983); they are common in slow-wave sleep because the membrane potential tends to be hyperpolarized (Hirsch et al., 1983; reviewed in McCormick and Bal, 1997). Crick (1984) suggested that as vigilance wanes, the membrane potential would hyperpolarize, enabling the calcium channel to trigger on the next retinal EPSP, yielding a burst of action potentials. This burst serves to alert the cortex and bring it back to a vigilant state and the LGN back to tonic mode. Potentially revolutionary was that thalamic neurons could have 'modes' (burst and tonic) associated with perceptual processes. The simple alternative was that bursts were reserved for sleep (when, of course, visual perception was not occurring) and the tonic mode for wakefulness. Experiments in the LGN of awake cats and monkeys established bursting occurs in wakefulness[5] (Guido and Weyand, 1994; Ramcharan et al., 2000; Weyand et al., 2001). Most significant was that burst probability could be manipulated by visual stimulation (Guido and Weyand, 1994; Weyand et al., 2001). Guido and Weyand (1994) noted that the first response to a drifting grating involving several cycles was more likely to produce a burst than subsequent cycles. This was consistent with the idea that the first stimulus issued the 'wake-up call' to the cortex, which then exerted its influence on the LGN neuron to convert from burst to tonic mode. While indicting, it was also true that stimulus size increased burst probability, an observation that the increase was as likely associated with manipulating on/off polarity as issuing a wake-up call (e.g. Coenen and

---

[5] Bursts of action potentials here are the consequence of activation of the low-threshold Ca^{++} current. However, under most extracellular recording situations, this underlying calcium event cannot be observed. Lu et al. (1992) did an intracellular study in which they observed that if two or more spikes occur in a cluster in which the first two interspike intervals are <4 ms, and that period is preceded by 100 ms of quiescence, the probability that the observed burst is riding the low-threshold Ca^{++} event is 99%. This is the statistical criteria most commonly used by extracellular investigators. In reality, the Ca^{++} depolarization can be observed extracellularly, but the electrode impedance should be high and the low-frequency cutoff should be low (e.g. 1 Hz; McCarley et al., 1983; Weyand, 2007).

Vendrik, 1972, show an obvious burst associated with on/off polarity reversal in their Figure 2). It is significant that McAlonan and colleagues (2008) showed robust enhancement with attention yet do not mention any link to bursting, even though Crick's (1984) paper is cited. Species and thalamic nuclei are significant variables regarding burst probability in wakefulness, limiting generalizability. In the LGN of the awake monkey, bursting is unusual (well below 1% of spikes; Ramcharan et al., 2005; Ruiz et al., 2006). In fact, among a cluster of dorsal thalamic nuclei including VPM, MGN, and pulvinar, the frequency of bursting in the LGN is the lowest by far (Ramcharan et al., 2005). Bursts in the LGN of the awake cat constitute 1% or fewer of spikes (Weyand et al., 2001; Weyand, 2007). In contrast, bursts in the awake rabbit's LGN appear frequent, under the right conditions exceeding 10% of spikes (Bezdudnaya et al., 2006). Further, Swadlow and Gusev (2001) showed that burst structure is particularly conducive to activating thalamocortical circuits in the awake rabbit. Whereas future investigations with different experimental design might align better with Crick's (1984) ideas, current results suggest that for the monkey at least, bursting in the LGN plays no special role in visual attention.

Implementation of the principle of graceful degradation

Efficient pattern recognition algorithms are not unidirectional. Neurons in layer VI of visual cortex provide a large feedback projection to the LGN and the adjacent TRN (~30% of synapses; Erisir et al., 1997; Van Horn et al., 2000). The mammalian retina has no equivalent circuit; it is essentially unidirectional. This is a big difference, providing an obvious substrate by which LGN activity separates from the retina. Similar to brainstem inputs to the LGN, anatomical and physiological studies devoted to unlocking the secrets of the corticogeniculate pathway also number in the 100s. The principle of graceful degradation comes from artificial intelligence and ties a rationale to this feedback loop. It effectively allows heuristics and context from a higher level (visual cortex) to shape processing at the lower level based on processes initiated at the lower level. In essence, it puts sensory input into the proper perceptual 'ballpark'. An initial inkling regarding structural identity (e.g. 'is that a cat or a meatloaf?') should be passed to the next stage, which then feeds back on that prior stage to improve the guess by providing context based on the pattern of initial activation within cortex (presumably, a broad parallel thalamocortical

volley, reflecting a visual scene) combined with higher-level heuristics associated with cognitive set (e.g. 'I'm looking at the kitchen counter'; reviewed in Gilbert and Li, 2013). Experimentally, with cortical feedback intact and visual stimuli employed that exceed the classical center and surround, LGN neurons are more selective in their responses relative to when visual cortex is inactivated (Sillito et al., 1993; Cudeiro and Sillito, 2006; Jones et al., 2012; Andolina et al., 2013; see review, Sillito et al., 2006). Particularly striking are changes in selectivity associated with two sets of gratings drifting in orthogonal directions: one confined to the classic center and surround the other, absent from the center/surround, but occupying the next ~20° (Sillito et al., 2006). Without cortex, responses were strong, but variable. With cortex intact, activity was significantly decreased, but responses were less variable (and more selective). The effect is reminiscent of Vinje and Gallant's (2002) observations in V1. Increasing stimulus size decreases response but increases information (bits/spike) and selectivity ('sparseness'). An additional observation is that with cortex intact, variance in initial visual responses is smaller and synchrony among LGN neurons of the same sign with disparate receptive fields markedly improves when a common edge cuts across both fields (Andolina et al., 2007).

Comment

Based on faith in the importance of sheer numbers, one might expect the contribution of the corticogeniculate path to LGN activity to be substantial. Therefore, initial studies indicating relatively paltry changes associated with inactivating visual cortex on LGN receptive fields (reversible inactivation: e.g. Baker and Malpeli, 1977; Geisert et al., 1981) must have been disappointing. These studies concentrated on changes in excitability associated with the classic center and surround, not the extended field, and not relative synchrony between LGN neurons. As highlighted above, robust effects emerged when stimuli included large stimuli that went well beyond the classic center and surround, and increased synchrony appeared when investigators began looking for such effects.

The observation that cortical inactivation could robustly affect LGN excitability, including synchrony, is a major separator of the retinal ganglion from the LGN neuron. This is particularly significant when coupled with the fact that LGN activity is exclusively coupled to its retinal drive. Cortex operates as an agent that prunes retinogeniculate activity into a more selective product; we assume it is anything but arbitrary. An impressive

observation regarding potential limits of this selectivity was provided by Richmond and colleagues (Gawne et al., 1991; McClurkin et al., 1991a,b). As a monkey fixated a spot, a checkerboard-like (Walsh) pattern was placed over the receptive field. The pattern was placed such that either a white or black rectangle covered the classic center; the rest of the pattern encompassed the classic surround and beyond. Sixty-four Walsh patterns were pseudo-randomly presented. What is most amazing is that each of the 64 patterns elicited a 'signature' response that emerged in the first 250 ms from stimulus onset, a temporal coding of a two-dimensional pattern. The signatures were reliable, repeatable, and for the most part, discriminable from the other patterns. Soon after, Golomb and colleagues (1994) showed that the major components observed by Richmond's group could be reproduced in the LGN of the paralyzed, anesthetized monkey, and further, these 'signatures' were largely a product of a linear convolution of the cell's receptive field (obtained via a spike-triggered average to construct the space-time receptive field [STRF]). Major components could be accounted for via linear mechanisms; no 'temporal code' need be invoked. To Golomb and colleagues (1994), the observed temporal pattern is the expected 'dissipation' of a linear mechanism responding to a sudden change in luminance across its receptive field. Both studies are intriguing. The latter study indicates the specificity that can evolve from linear interactions alone; the former study serves as a catalyst to rethink coding in the early visual system. Whereas the size of cortical downflow can represent 25–30% of synapses onto relay neurons (Van Horn et al., 2000), the fact that these neurons are orientation selective (and often, highly so, Tsumoto and Suda, 1980) indicates they are not likely to be particularly active at any time (Macknik and Martinez-Conde, 2009). This contrasts with retinogeniculate synapses, which tend to be very active (20–90 Hz), providing yet another reason for the weak effects of individual corticogeniculate neurons on LGN activity.

Temporal diversity

Projection neurons in the LGN show significant diversity in latency to visual response, much more than one observes in retina. This is certainly true in the cat (Sestokas and Lehmkuhle, 1988; Wolfe and Palmer, 1998), but less apparent in monkey (e.g. Maunsell et al., 1999). In the cat, these differences well exceed the expected diversity associated with conduction differences between X-, Y-, and W-cells. A likely source of this temporal diversity is attributable to the extensive fraction of inhibitory interneurons that also receive direct retinal input and synapse on these projection cells (feedforward inhibition). Dominating feedforward inhibition creates lagged cells (Mastronarde, 1987a,b), a type of neuron that does not exist in the retina. Lagged cells are controversial, as they often seem ignored. For example, Sherman and Guillery (2004) review the synaptic organization of the LGN, yet lagged cells do not appear. Considering that 30–40% of LGN X-cells may be lagged (Mastronarde, 1987b; Humphrey and Weller, 1988a), this is bizarre. Lagged cells would appear perfect for establishing temporal diversity as they are dominated by feedforward inhibition. Feedforward inhibition is well accepted, even if lagged cells are not. A lagged cell receives a driving input from retina, but that drive is commonly thwarted by the disynaptic inhibition emerging from that retinal input driving an adjacent inhibitory interneuron, which then inhibits the lagged cell (Figure 3A; Mastronarde, 1987b). As Mastronarde (1987a) describes, lagged and nonlagged cells lie on a continuum, although this distribution is distinctly bimodal, with few neurons between. The lagged/nonlagged nature of most X-cells can be readily distinguished by their response to a spot presented to the receptive field center. For an on-center cell, a 1-s on-period in the nonlagged cell shows a transient large increase in the first 100 ms followed by a steady tonic increase for the remaining period. In contrast, the on-center lagged cell tends to show an increase in activity but lacks the initial transient. The big difference is that stimulus offset typically yields a large transient response in the lagged cell that is absent in the nonlagged cell. Mastronarde (1987b) showed that lagged cells project to visual cortex via slowly conducting axons, a feature establishing their existence independent of response properties. Yet another independent feature was anatomical: glomeruli were much more numerous on lagged than nonlagged X-cells (Humphrey and Weller, 1988b). A likely reason lagged cells are not commonly reported is that they are small (Humphrey and Weller, 1988a), making them harder to isolate, and their responses to visual stimuli are confusing because of their dominance by inhibition. Nonetheless, several laboratories (besides Mastronarde) seem capable of finding them regularly (Heggelund and Harveit, 1990; Saul and Humphrey, 1990; Kwon et al., 1991; Saul, 2009; Vigeland et al., 2013) and they have been observed in both cat and monkey.

Temporal diversity underlies two putative LGN functions: temporal decorrelation to achieve efficient coding of retinogeniculate signals and temporal diversity to create a substrate for constructing direction-selective neurons in visual cortex.

Temporal diversity to achieve efficient coding

Ecological theories of perception hold a common theme: the statistical properties of the animal's environment prejudice the sensory envelope that defines the animal's sensitivities. Natural images, the visual patterns associated with living in the natural environment, have a number of statistical properties that set them apart from a much larger set of possible images (e.g. Simoncelli and Olshausen, 2001; Doyle and Csete, 2011). The texture of natural images is highly redundant. When we gaze around a room or stare outside, adjacent points of any current image are likely similar intensity, i.e. highly correlated. Because we fixate for several hundred milliseconds, and because images during the fixation tend to be highly static, redundancy can be applied to the temporal as well as spatial domains (Dong and Atick, 1995b; in fact, eye movements are by far the biggest source of image decorrelation). A reasonable hypothesis is that an important job of the early visual system (retina, LGN) is to reduce this redundancy (spatial and temporal correlations), recoding such signals into a decorrelated, efficient form (Barlow, 1961). The concentrically organized receptive field that dominates the retina and LGN (and extends into layer IV of monkey visual cortex) efficiently reduces redundancies in the spatial and, to a lesser extent, the temporal domain. The discovery of lagged cells (Mastronarde, 1987a,b) prompted Dong and Atick (1995a) to propose that LGN concentric neurons and lagged cells, in particular, might be strongly engaged in temporal decorrelation. Dan and colleagues (1996) tested this idea on single nonlagged LGN X-cells. Presenting video images (from 'Casablanca') yielded a distribution of interspike intervals that were decorrelated or 'whitened'; the autocorrellogram of spike times was flat at low frequencies, meaning the distribution of interspike intervals was rich. This would represent an efficient code of the natural environment (basically, the stream of spikes would contain many 'words' because of the diversity of interspike intervals). In contrast, a white noise stimulus used as a control was rich in the space-time domain (spatiotemporally diverse) but did not possess the statistical properties of natural images (space-time correlations were near zero). The resulting autocorrellograms were not flat. These results favored an interpretation in which the visual system had evolved to optimally encode natural image statistics.

Comment

The study by Dan and colleagues (1996) has been influential, but three points are worth noting. First, the study was done on LGN cells; it was implied, but never tested, that whitening was an achievement of LGN circuits. Pitkow and Meister (2012) concluded that natural images decorrelate the spike train of retinal ganglion cells (temporal domain) and correlations among adjacent retinal ganglion cells also drop in response to natural images (control was spatiotemporal noise similar to that used by Dan et al., 1996). Whereas these results in retina were intriguing, they were obtained from *in vitro* preparations (salamander and monkey retinae), and the contrast was high. The only *in vivo* study to observe a transform from a nonwhitened retina to a whitened LGN spike train has only been reported in abstract. Second, Dan and colleagues only encountered nonlagged X-cells, so we do not know how lagged X-cells or Y-cells would respond. Third, the Dan et al. study was spectacularly successful in predicting LGN spikes from a linear model constructed with luminance fixed and contrast held within a linear range. Since luminance and contrast gain control are constantly engaged in the real world (Mante et al., 2005), it is of interest to know the degree to which the LGN spike train decorrelates under more realistic conditions (which would also include eye movements).

Temporal diversity as a substrate for constructing direction-selective neurons in visual cortex

Direction-selective neurons can emerge from several different wiring schemes (reviewed in Borst and Helmstaedter, 2015), but all depend on a comparison of responses separated in space and time. Saul and Humphrey (1990, 1992; Humphrey and Saul, 2002; Saul, 2008) have provided evidence that combining lagged and nonlagged cell inputs in cortex can generate direction-selective neurons. The complementary nature of responses of lagged and nonlagged LGN neurons to temporally modulated luminance spots provides a potential mechanism of generating direction selectivity. When response timing of spatially distinct inputs to a cortical neuron differs by a quarter cycle, the components of a stimulus that differ by about a quarter cycle in space between the inputs generates constructive interference in one direction as the spatial and temporal differences cancel, whereas a stimulus moving in the opposite direction generates destructive interference as the quarter cycles add to a half cycle. Such phase-dependent addition/subtraction is referred to as spatiotemporal quadrature (Watson and Ahumada, 1985). As Saul (2008) notes, finding quarter-cycle offset in the spatial domain

is relatively easy (i.e. spatially offset receptive fields). Quarter-cycle differences in the time domain are more difficult because at low frequencies, timing differences between the two inputs must vary by >100 ms and must vary dramatically across a small range of low temporal frequencies, a tall order. But the potent feedforward inhibition that dominates the lagged cell's response supports such delays (phase shifts), resulting in response profiles in or near spatiotemporal quadrature (it need not be exact). Variance in visual latencies contribute to this as well because of the temporal integration required to implement the phase shifts (Saul, 2008).

Comment

There has been significant interest in how direction-selective neurons are constructed, beginning with Barlow and Levick's (1965) classic analysis of direction-selective neurons in the rabbit retina. Efforts by Saul and Humphrey (Saul and Humphrey, 1992; Humphrey and Saul, 2002; Saul, 2008) indicate directional selectivity can emerge from the diversity in response timing associated with lagged and nonlagged LGN cells. Whereas most cortical models involve inhibitory elements at the level of cortex to implement direction selectivity, the inhibition here emerges from the powerful feedforward inhibition at the level of the LGN that defines the lagged cell (Mastronarde, 1987b). It seems a clever rationale for the observed large timing differences observed in the LGN. Evidence that the system uses these timing differences is offered by studies that abolish inhibition in visual cortex (e.g. Murthy and Humphrey, 1999). Whereas directional selectivity suffers, there is a residual component left, presumably attributable to the spatiotemporal quadrature established between converging lagged and nonlagged LGN cells onto cortex.

Oculomotor functions

Mixing oculomotor signals with visual activity at the level of the LGN could be used for at least three purposes. One is to effectively cancel vision during eye movements: saccadic suppression. Related is the use of motor signals to disambiguate self-movement from movement of the environment: retinal reafference. Third, oculomotor signals can be used to alter visual responsiveness for the purpose of constructing a head-centered frame of reference. Retinal signals are in retinal coordinates. Many things we do (e.g., reaching) must be translated into an egocentric frame. A head-centered frame is a first step.

Saccadic suppression

Mechanisms exist to suppress signals generated by the retinae when the eyes move. Perception is exceptionally poor during these eye movements, and Zeitgeist holds that our perception of the world is constructed from the series of retinal 'snapshots' taken during the fixation episodes between saccades. Oculomotor signals here could serve two purposes: one would be to simply cancel signals during saccades (which would presumably create a lot of blur due to activation of the photoreceptors), and second, oculomotor signals could be used to disambiguate potential perceived movement generated by eye movements (sometimes referred to as retinal reafference) from signals associated with movement in the environment. Classically, oculomotor signals can emerge from two sources: a corollary discharge, in which a copy of a motor output signal is sent to the LGN, or proprioceptive signals (e.g., from muscle spindle receptors) that reach the LGN. There is evidence for both types of signals (e.g. Donaldson and Dixon, 1980; Swadlow and Weyand, 1987; Lo, 1988; Lal and Friedlander, 1989, 1990; Cucchiaro et al., 1993; Schmidt, 1996; see below). The simplest test to implicate oculomotor involvement is to remove vision and determine if activity shifts with eye movements. When Lee and Malpeli (1998) recorded single neurons in the LGN in the dark, they found weak signals associated with saccades that could only be observed by synchronizing 50+ saccades (and this was for their 'sensitive' cells, cf. Figure 5, Lee and Malpeli, 1998). Lee and Malpeli (1998) observed that a weak but reliable suppression begins >100 ms preceding the saccade. This suppression peaks near saccade onset and is replaced by a sizeable facilitation that peaks at the end of the saccade. Similar, but more robust, results were also obtained in the monkey by Royal and colleagues (2006). Reid and colleagues (Reppas et al., 2002) took a different approach. A monkey made saccades to small targets presented on a screen of zero contrast but which was constantly and randomly changing luminance. Because switching luminance was random, the visual response to that switching should be randomly distributed across the saccade. Synchronizing activity to movement onset could probe excitability changes associated with saccades. All three groups obtained similar functions to that described above, and these excitability shifts occurred in both light and dark. The depression prior to saccade onset indicates the LGN is privy to an oculomotor signal (corollary discharge) as well as whatever additional components from retina or proprioceptive signals can be added once the saccade starts.

Comment

Recent work in the retina indicates that some ganglion cells are sensitive to global shifts in retinal signals, the kind of signals that would be associated with saccadic eye movements (Olveczky et al., 2003; Roska and Werblin, 2003). Such observations undermine the idea that oculomotor signals are needed at all to disambiguate self-motion from movement of the environment. This perceived need of 'efference mediation of vision' for this purpose is hundreds of years old and depends on the idea that vision is impoverished on these matters. In fact, careful analysis of visual texture indicates that this ambiguity is largely ethereal (Turvey, 1979). The recent work cited above (Olveczky et al., 2003; Roska and Werblin, 2003) reinforces this idea; the retina knows the difference. We do not need oculomotor signals to disambiguate self from environmental movement, but we do apparently use such signals to suppress vision during saccades.

Perhaps a bigger story regarding eye movements and visual computation is the emerging role of microsaccades (movements <1°) in generating spikes at the level of the LGN (Martinez-Conde et al., 2002) and the related idea that microsaccades serve to enrich information from the visual environment (Martinez-Conde et al., 2004, 2006, 2013; Rucci et al., 2007; McCamy et al., 2014; Rucci and Victor, 2015). Whereas we make large saccades to foveate interesting pieces of our environment, the eye is never still during 'fixations' (i.e. periods between saccades). Far from being an artifact, 'perimicrosaccadic' periods are a major source of spike generation during fixation (Martinez-Conde et al., 2002), and these 'tremors' actually enrich available information by correlating spike activity to enrich and sharpen borders (Rucci and Victor, 2015). This is an emerging area because our past enquiry into the mechanisms of early vision have been heavily invested in the paralyzed eye (to control stimulus variability), and even in awake animals, these microsaccades were often either not observed due to technical limitations or simply viewed as noise (Martinez-Conde et al., 2004, 2006).

The contribution of spikes associated with microsaccades is significant. As Martinez-Conde and her colleagues (Martinez-Conde et al., 2002) indicate, these microsaccades generate 'bursts' of action potentials. However, these bursts likely have nothing to do with activation of calcium channels, these bursts are generated by interactions of the motor system with the retina (i.e. sweeping the retina across visual texture improves visual resolution; e.g. Greschner et al., 2002). Given the current inability to tie calcium-related bursts to perception in the LGN (reviewed above), these 'bursts' are much more likely to be relevant to visual perception.

Head-centered coordinates

Whereas signals from the retina are used to tell us what is out there, additional circuits are needed to tell us where relative to our current position (e.g. 'where are those things relative to me?'). This is a significant computational problem: the retina is attached to the back of the orbit and swivels in a socket that sits in a swiveling head connected to a body capable of pitch, yaw, and roll. Initial computation involves combining retinal signals with eye position signals to construct a representation in head-centered coordinates. Apparently, this construction begins in the LGN. In a novel preparation, Lal and Friedlander (1989, 1990) showed that visual response to a stimulus presented to one eye could be modulated by manipulating the position of the other eye. The cat was paralyzed and anesthetized, and the manipulated eye was closed or treated with tetrototoxin. The effects were robust and orderly. Though such disparate eye positions used could never occur naturally, it was remarkable that any effects were observed at all. To ensure that these eye signals were real, Lal and Friedlander (1990) reversibly blocked the ophthalmic division of the trigeminal ganglia, abolishing the effect. Although Weyand and Malpeli (1993) showed systematic influence of gaze on visual responses in area 17 of the awake, behaving cat (which should be no surprise considering Lal and Friedlander's results), it would be important to demonstrate gaze-related effects in the LGN of the awake, behaving animal. Thus far, only minor or negative effects have appeared in abstract form.

The LGN is not a simple relay

Upon observing that single retinal axons in the monkey appeared to make contact with but a single LGN neuron, Glees and LeGros Clark (1941) felt compelled to remark '…it seems that the cells of the lateral geniculate body have one function only to perform–to serve as simple relays for retinal impulses on their way to visual cortex' (p. 304). This pessimism can be replaced with a much different picture, the focus of this review and summarized here:

(1)   Retinal inputs to the LGN are sorted by eye, functional group, and center polarity. This 'housekeeping' allows nonretinal inputs simpler access to

homogenous LGN populations. For example, corticogeniculate cells retain axons selectively target magnocellular, parvocellular, and koniocellular zones. Second, effects of EEG arousal on activity can be manipulated by LGN layer.

(2, 3) Retinogeniculate wiring introduces diversity. Retinal inputs can (2) multiplex to drive multiple LGN neurons and/or (3) integrate with other retinal inputs, creating receptive fields that have no retinal counterpart. Many of these retinal inputs participate in feedforward inhibition, a disynaptic inhibition onto relay cells that can alter the strength of the receptive field surround and/or alter timing of retinogeniculate transmission. Feedforward inhibition serves to create a neuron type, the lagged cell that has no retinal counterpart. Intrinsic membrane properties of LGN neurons alter the nature of retinogeniculate transmission, creating additional diversity.

(4) LGN neurons have their own luminance/contrast gain control, altering retinogeniculate efficacy.

(5) State alters the efficacy of retinogeniculate transmission: efficacy increases with level of alertness. This increased efficacy can have a spatial component, demonstrating selective attention. Because these state-dependent effects appear tied to visually driven activity, state effectively amplifies retinal signals in an activity-dependent manner.

(6) LGN neurons receive a large 'feedback' input from visual cortex. This pathway increases the selectivity of LGN neurons, especially when visual texture that differs from that presented to the center is presented to the extra-classical surround. Further, the presence of this pathway enhances synchronicity among different LGN neurons that are stimulated by a common edge.

(7) Temporal diversity induced by feedforward inhibition can be used to temporally decorrelate response to natural images. This decorrelated form provides a more efficient code of natural scenes.

(8) Temporal diversity induced by feedforward inhibition creates a substrate for creating directionally selective neurons in visual cortex and depends heavily on the properties of lagged cells.

(9) Eye movements alter the efficacy of retinogeniculate transmission. A depression (reduced efficacy) begins ~100 ms prior to a saccade, continues to saccade onset, and then turns to an excitation whose peak is synchronized with saccade end. The fact that the depression precedes saccade onset indicates that the source of these signals is neither retinal nor proprioceptive.

(10) Eye position can alter visual responsiveness. Vision captures not only what's out there, but where relative to current position. Interactions of visual response by eye position indicate the LGN is involved in constructing a head-centered frame of reference, a first step in obtaining an egocentric frame.

This summarizes the 10 functions of the LGN. With the exception of the first function, all of the remaining can influence retinogeniculate efficacy, or LGN spike probability. This not only presents a more complex picture of transmission, but it also indicates understanding the retinogeniculate transform requires the awake, behaving animal.

Experiments: separating retina from LGN

Hubel and Wiesel (1961) made a key observation regarding differences between retina and LGN. As they monitored LGN spikes and the driving S-potential, they presented discs of varying sizes centered over the cell's receptive field. Increasing disc size decreases retinogeniculate efficacy, and they concluded that LGN receptive fields have more powerful surrounds. More recent studies have applied noise[6] stimuli and/or information theory to assess retinogeniculate transmission, concluding that each LGN spike contains ~20–50% more information (in bits/spike) than the driving retinal spike does (Rathbun et al., 2010; Sincich et al., 2009; Uglesich et al., 2009). All of these studies were done in paralyzed, anesthetized animals. The ability to directly measure retinogeniculate efficacy is powerful as it so directly contrasts retinal and LGN activity. Since many of the functions listed above can be appreciated only in the awake, behaving animal, and because visual excitability in the early vision is depressed by anesthesia (McIlwain, 1964; Alitto et al., 2011), it makes sense to make that a priority. Two related experiments could provide stark contrast between operations of the LGN and retina. Ideally, both would simultaneously monitor LGN

---

6 It is easy to treat the receptive field as stationary; i.e. delivery of a punctate stimulus s at time *t* will deliver nearly the same response every time. In fact, stationary properties are limited, antecedent conditions commonly alter stationarity. Because noise is uncorrelated in space and time, stimuli consisting of noise do not carry antecedent bias, yielding a more objective assessment of response under all conditions. For a historical review of this shift in view of receptive fields (as a space-time filter), see DeAngelis et al. (1995) or Ringach (2004). For a succinct discussion of the impetus and merits of various noise stimuli, see Reid et al. (1997).

activity and its retinal drive. Experiment 1 quantifies differences between retinal and LGN activity during presentation of videos of natural images; experiment 2 quantifies differences between retinal and LGN activity during presentation of complex shapes (Walsh patterns; discussed above). Both experiments would monitor eye position (and gaze) with the head fixed. By monitoring activity in retina and LGN using natural image videos (e.g. movies of animals in the wild), experiment 1 can determine the degree to which the LGN spike train is whitened relative to retina, providing a direct demonstration of potential temporal decorrelation and efficient coding (Dan et al., 1996). In addition, reverse correlation techniques can be used to recover the STRF for both retina and LGN. Various nonlinear filters can then be applied to improve model accuracy (e.g. Theunissen et al., 2000, 2001; David et al., 2004; Mante et al., 2008). The first thee references comment on the increased predictive power associated with using natural images to construct the receptive field over more standard methods that are more mathematically tractable (e.g. gratings, noise). Because eye position is monitored, contributions of microsaccade and saccades to neural excitability can be included. Further, both the retina and LGN spike trains can be analyzed for information transmission using standard methods (e.g. Strong et al., 1998). Experiment 2 would provide a direct method of contrasting the encoding capabilities of LGN and retinal ganglion neurons. Because LGN neurons contain more nonlinearities in their responses than retinal ganglion cells do (e.g. Duong and Freeman, 2008; Solomon et al., 2010), they are more likely to emerge as more discriminating. It remains an intriguing question how much separation between retina and LGN one can measure using this method. These are difficult experiments. The monkey might be more manageable than the cat in achieving better gaze control and longer sessions (more data), but recording S-potentials in the monkey is more difficult than in the cat (cf. Lee et al., 1983). Experiments would be valuable in either species. An alternative would be to record LGN neurons and optic tract axons separately. Recording from single LGN neurons is fairly routine; recording form optic tract axons even in the monkey over extended periods in the awake monkey is feasible (Alitto and Usrey, 2008).

The place of the LGN in vision

Vision is usually described as a pattern recognition problem, with a hierarchical structure. Just one synapse removed from the retina, the LGN is regarded as a 'low-level' player in visual system design. The job of the retina is to capture spatial and temporal dynamics without committing to any specific feature.[7] Such neurons are referred to as dense encoders to distinguish them from sparse encoders (feature detectors; Olshausen and Field, 2004) found in visual cortex. There is a chain in which the more removed from retina, the more selective the neuron becomes. Classically, perception proceeds in a bottom-up fashion, from simple visual attributes (e.g. light/dark) to complex (e.g. face selective neurons). Because LGN receptive fields have the concentric organization similar to retina, and because retina is the exclusive drive for LGN neurons, the LGN is also a dense encoder. But there are three important qualifiers. First, the bottom-up chain is modulated by a top-down chain, heuristics that deal with context. We seem to be only beginning to appreciate how powerful top-down effects are in shaping new information coming through the retina and the extent of its 'creep' into the early stages of vision (e.g. Gilbert and Li, 2013). Top-down influence is strong in visual cortex, including primary visual cortex. Primary visual cortex is the source of a major projection to the LGN and is a source of input that the retina does not possess. The argument has been made above that this feedback pathway increases the selectivity of the LGN neuron. Because LGN spikes occur if and only if there is an antecedent retinal spike, this increased selectivity emerges via a judicious pruning or editing of the retinal spike train. Thus, the LGN may still be dense, but it is less dense than its retinal counterpart. This 'less dense' translates to a temporal code that can be highly selective (e.g. Gawne et al., 1991; McClurkin et al., 1991a,b; Golomb et al., 1994). Our usual parsing of dense and sparse coding lies along spatiotemporal attributes

---

7 Early cells do not 'commit' to features because such commitment would limit the computational power of later stages and, as pointed out above, circuit space to build sophisticated circuits in retina and LGN is limited. Nonetheless, the degree to which the visual system adheres to this hierarchy of finickyness is debatable (cf. Gollisch and Meister, 2010). The geniculocortical pathway seems to specifically exclude fancy cells found in the retina. Species in which directionally selective retinal ganglion cells are abundant (e.g. 25% in rabbit; Caldwell and Daw, 1978) have either few (1%; Swadlow and Weyand, 1985) or no (squirrel; Van Hooser et al., 2003) such neurons in the LGN. Further, it appears that the initial processing neuron in the visual cortex of the tree shrew (Van Hooser et al., 2013) and probably all primates is dominated by concentric neurons (e.g. Blasdel and Fitzpatrick, 1984). Thus, the retina may possess some fancy response properties, but invested properties such as direction selectivity are not bound for visual cortex among the 'smarter' animals. This does not, however, undermine the idea that retinal ganglion and LGN cells can be sophisticated; it is just that their sophistication emerges as a temporal code.

that increase or decrease spike probability; i.e. that feature is present because that neuron produced a spike. Temporal coding is an alternative: features are encoded in the temporal distribution of spikes (cf. Keat et al., 2001; Liu et al., 2001; Fairhall et al., 2006).

In summary, much of this review has concentrated on separating the LGN from the retina. Largely because of technical limitation, most of these studies comparing retinogeniculate differences were done in paralyzed, anesthetized animals. These studies negate or minimize potential differences associated with eye movements (saccades and microsaccades), state, the potential significance of natural image stimuli, and the degree to which the encoding process is passed as a temporal code vs. simply the numbers of spikes. All of these complicate analyses, yet all of these have a compelling bearing on LGN function.

References

Ahlsen, G. (1984). Brain stem neurones with differential projections to functional subregions of the dorsal lateral geniculate complex in the cat. Neuroscience *12*, 817–838.

Ahlsen, G., Lindstrom, S., and Lo, F.-S. (1984). Inhibition from the brain stem of inhibitory interneurones of the cat's dorsal lateral geniculate nucleus. J. Physiol. *347*, 593–609.

Alitto, H.J. and Usrey, W.M. (2008). Origin and dynamics of extraclassical suppression in the lateral geniculate nucleus of the macaque monkey. Neuron *57*, 135–146.

Alitto, H.J., Moore, B.D., Rathbun, D.L., and Usrey, W.M. (2011). A comparison of visual responses in the lateral geniculate nucleus of alert and anaesthetized macaque monkeys. J. Physiol. *589*, 87–99.

Alonso, J.M., Usrey, W.M., and Reid, R.C. (1996). Precisely correlated firing in cells of the lateral geniculate nucleus. Nature *383*, 815–819.

Alonso, J.M., Usrey, W.M., and Reid, R.C. (2001). Rules of connectivity between geniculate cells and simple cells in cat primary visual cortex. J. Neurosci. *21*, 4002–4015.

Andolina, I.M., Jones, H.E., Wang, W., and Sillito, A.M. (2007). Corticothalamic feedback enhances stimulus response precision in the visual system. Proc. Natl. Acad. Sci. USA *104*, 1685–1690.

Andolina, I.M., Jones, H.E., and Sillito, A.M. (2013). Effects of cortical feedback on the spatial properties of relay cells in the lateral geniculate nucleus. J. Neurophysiol. *109*, 889–899.

Baker, F.H. and Malpeli, J.G. (1977). Effects of cryogenic blockade of visual cortex on the responses of lateral geniculate neurons in the monkey. Exp. Brain Res. *29*, 433–444.

Barlow, H.B. (1961). Possible principles underlying the transformation of sensory messages. Sensory Communication. W.A. Rosenblish, ed. (Cambridge: MIT), 217–234.

Barlow, H.B. and Levick, W.R. (1965). The mechanism of directionally selective units in rabbit's retina. J. Physiol. *178*, 477–504.

Bezdudnaya, T., Cano, M., Bereshpolova, Y., Stoelzel, C.R., Alonso, A.-M., and Swadlow, H.A. (2006). Thalamic burst mode and inattention in the awake LGNd. Neuron *49*, 421–432.

Bishop, P.O., Burke, W., and Davis, R. (1962). The interpretation of the extracellular response of single lateral geniculate cells. J. Physiol. *162*, 451–472.

Blasdel, G.G. and Fitzpatrick, D. (1984). Physiological organization of layer 4 in macaque striate cortex. J. Neurosci. *4*, 880–895.

Blitz, D.M. and Regehr, W.G. (2005). Timing and specificity of feedforward inhibition within the LGN. Neuron *45*, 917–928.

Borghuis, B.G., Ratliff, C.P., Smith, R.G., Sterling, P., and Balasubramanian, V. (2008). Design of a neuronal array. J. Neurosci. *28*, 3178–3189.

Borst, A. and Helmstaedter, M. (2015). Common circuit design in fly and mammalian motion vision. Nat. Neurosci. *18*, 1067–1076.

Bowling, D.B. and Michael, C.R. (1980). Projection patterns of single physiologically characterized optic tract fibres in cat. Nature *286*, 899–902.

Bowling, D.B. and Michael, C.R. (1984). Terminal patterns of single physiologically characterized optic tract fibers in the cat's lateral geniculate nucleus. J. Neurosci. *4*, 198–216.

Briggs, F. and Usrey, W.M. (2009). Parallel processing in the corticogeniculate pathway of the macaque monkey. Neuron *62*, 135–146.

Brown, T.M., Gias, C., Hatori, M., Keding, S.R., Semo, M., Coffey, P.J., Gigg, J., Piggins, H.D., Panda, S., and Lucas, R.J. (2010). Melanopsin contributes to irradiance coding in the thalamocortical visual system. PLoS Biol. *8*, e10000558.

Bruno, R.M. and Sakmann, B. (2006). Cortex is driven by weak but synchronously active thalamocortical synapses. Science *312*, 1622–1627.

Burke, W. and Cole, A.M. (1978). Extraretinal influences on the lateral geniculate nucleus. Rev. Physiol. Biochem. Pharmacol. *80*, 105–166.

Butler, A.B. (1994a). The evolution of the dorsal thalamus of jawed vertebrates, including mammals: cladistic analysis and a new hypothesis. Brain Res. Rev. *19*, 29–65.

Butler, A.B. (1994b). The evolution of the dorsal pallium of amniotes: cladistics analysis and a new hypothesis. Brain Res. Rev. *19*, 66–101.

Butler, A.B. (2008). Evolution of the thalamus: a morphological and functional review. Thalamus Relat. Syst. *4*, 35–58.

Caldwell, J.H. and Daw, N.W. (1978). New properties of rabbit retinal ganglion cells. J Physiol. *276*, 257–276.

Casagrande, V.A., Sary, G., Royal, D., and Ruiz, O. (2005). On the impact of attention and motor planning on the lateral geniculate nucleus. Prog. Brain Res. *149*, 11–29.

Cheng, H., Chino, Y.M., Smith, E.L., 3rd, Hamamoto, Y., and Yoshida, K. (1995). Transfer characteristics of lateral geniculate nucleus X neurons in the cat: effects of spatial frequency and contrast. J. Neurophysiol. *74*, 2548–2557.

Cleland, B.G. and Lee, B.B. (1985). A comparison of visual responses of cat lateral geniculate nucleus neurones with those of ganglion cells afferent to them. J. Physiol. *369*, 249–268.

Cleland, B.G., Dubin, M.W., and Levick, W.R. (1971). Simultaneous recording of input and output of lateral geniculate neurones. Nature New Biol. *231*, 191–192.

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

Coenen, A. and Vendrik, A. (1972). Determination of transfer ratio of cat's geniculate neurons through quasi-intracellular recordings and the relation with the level of alertness. Exp. Brain Res. *14*, 227–242.

Conley, M. and Raczkowski, D. (1990). Sublaminar organization within layer VI of the striate cortex in Galago. J. Comp. Neurol. *302*, 425–436.

Conley, M., Penny, G.R., and Diamond, I.T. (1987). Terminations of individual optic tract fibers in the lateral geniculate nuclei of *Galago crassicaudatus* and *Tupaia belangeri*. J. Comp. Neurol. *256*, 71–87.

Crick, F. (1984). Function of the thalamic reticular complex: the searchlight hypothesis. Proc. Natl. Acad. Sci. USA *81*, 4586–4590.

Cucchiaro, J.B., Uhlrich, D.J., and Sherman, S.M. (1993). Ultrastructure of synapses from the pretectum in the A-laminae of the cat's lateral geniculate nucleus. J. Comp. Neurol. *334*, 618–630.

Cudeiro, J. and Sillito, A. (2006). Looking back: corticothalamic feedback and early visual processing. Trends Neurosci. *29*, 298–306.

Dan, Y., Atick, J., and Reid, R.C. (1996). Efficient coding of natural scenes in the lateral geniculate nucleus: experimental test of a computational theory. J. Neurosci. *16*, 3351–3362.

Dan, Y., Alonso, J.-A., Usrey, W.M., and Reid, R.C. (1998). Coding of visual information by precisely correlated spikes in the lateral geniculate nucleus. Nat. Neurosci. *1*, 501–507.

Datskovskaia, A., Carden, W.B., and Bickford, M.E. (2001). Y retinal terminals contact interneurons in the cat dorsal lateral geniculate nucleus. J. Comp. Neurol. *43*, 85–100.

David, S.V., Vinge, W.E., and Gallant, J.L. (2004). Natural stimulus statistics alter the receptive field structure of V1 neurons. J. Neurosci. *24*, 699–7006.

DeAngelis, G.C., Ohzawa, I., and Freeman, R.D. (1995). Receptive-field dynamics in the central visual pathways. Trends Neurosci. *18*, 451–458.

Donaldson, I.M.L. and Dixon, D.A. (1980). Excitation of units in the lateral geniculate and contiguous nuclei of the cat by stretch of extrinsic ocular muscles. Exp. Brain Res. *38*, 245–255.

Dong, D.W. and Atick, J. (1995a). Temporal decorrelation: a theory of lagged and nonlagged responses in the lateral geniculate nucleus. Network: Comput. Neural Sys. *6*, 159–178.

Dong, D.W. and Atick, J. (1995b). Statistics of natural time-varying images. Network: Comput. Neural. Syst. *6*, 345–358.

Doyle, J.C. and Csete, M. (2011). Architecture, constraints and behavior. Proc. Natl. Acad. Sci. USA *108* (Suppl. 3), 15624–15630.

Dreher, B. and Sefton, A.J. (1979). Properties of neurons in cat's dorsal lateral geniculate nucleus: a comparison between medial interlaminar and laminated parts of the nucleus. J. Comp. Neurol. *183*, 47–64.

Dreher, B., Sefton, A.J., Ni, S.Y.K., and Nisbett, G. (1985). The morphology, number, distribution and central projections of class I retinal ganglion cells in albino and hooded rats. Brain Behav. Evol. *26*, 10–48.

Dubin, M.W. and Cleland, B.G. (1977). Organization of visual inputs to interneurons of lateral geniculate nucleus of the cat. J. Neurophysiol. *40*, 410–427.

Duong, T. and Freeman, R.D. (2008). Contrast sensitivity is enhanced by expansive nonlinear processing in the lateral geniculate nucleus. J. Neurophysiol. *99*, 367–372.

Enroth-Cugell, C. and Robson, J.G. (1966). The contrast sensitivity of retinal ganglion cells in the cat. J. Physiol. *187*, 517–552.

Erisir, A., Van Horn, S.C., and Sherman, S.M. (1997). Relative number of cortical and brainstem inputs to the lateral geniculate nucleus. Proc. Natal. Acad. Sci. USA *94*, 1517–1520.

Fairhall, A.L., Burlingame, C.A., Narasimhan, R., Harris, R.A., Puchalla, J.L., and Berry, M.J. (2006). Selectivity for multiple stimulus features in retinal ganglion cells. J. Neurophysiol. *96*, 2727–2738.

Famiglietti, E.V. Jr, and Peters, A. (1972). The synaptic glomerulus and the intrinsic neuron in the dorsal lateral geniculate nucleus of the cat. J. Comp. Neurol. *144*, 285–334.

Fitzpatrick, D., Usrey, W.M., Schofield, B.R., and Einstein, G. (1994). The sublaminar organization of corticogeniculate neurons in layer 6 of macaque striate cortex. Vis. Neurosci. *11*, 307–315.

Gawne, T.J., McClurkin, J.W., Richmond, B.J., and Optican, L.M. (1991). Lateral geniculate neurons in behaving primates III. Response predictions of a channel model with multiple spatial-to-temporal filters. J. Neurophysiol. *66*, 809–823.

Geisert, E.E., Langsetmo, A., and Spear, P.D. (1981). Influence of the cortico-geniculate pathway on response properties of cat lateral geniculate neurons. Brain Res. *208*, 409–415.

Gilbert, C.D. and Li, W. (2013). Top-down influences on visual processing. Nat. Rev. Neurosci. *14*, 350–363.

Glees, L. and LeGros Clark, W.E. (1941). The termination of optic fibres in the lateral geniculate nucleus of the monkey. J. Anat. *75*, 295–308.

Gollisch, T. and Meister, M. (2010). Eye smarter than scientists believed: neural computations in circuits of the retina. Neuron *65*, 150–164.

Golomb, D., Kleinfeld, D., Reid, R.C., Shapley, R.M., and Shraiman, B.I. (1994). On temporal codes and the spatiotemporal response of neurons in the lateral geniculate nucleus. J. Neurophysiol. *72*, 2990–3003.

Greschner, M., Bongard, M., Rujan, P., and Ammermuller, J. (2002). Retinal ganglion cell synchronization by fixational eye movements improves features estimation. Nat. Neurosci. *5*, 341–347.

Grieve, K.L. (2005). Binocular visual responses in cells of the rat dLGN. J. Physiol. *566*, 119–124.

Guido, W. and Weyand, T. (1994). Burst responses in thalamic relays cells of the awake behaving cat. J. Neurophysiol. *74*, 1782–1786.

Guillery, R.W. (1966). A study of Golgi preparations from the dorsal lateral geniculate nucleus of the adult cat. J. Comp. Neurol. *128*, 25–50.

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

Guillery, R.W., Geisert, E.E., Polley, E.H., and Mason, C.A. (1980). An analysis of the retinal afferents to the cat's medial interlaminar nucleus and to its rostral thalamic extension, the 'geniculate wing'. J. Comp. Neurol. *194*, 117–142.

Hamori, J., Pasik, P., and Pasik, T. (1983). Differential frequency of P-cells and I-cells in magnocellular and parvocellular laminae

of monkey lateral geniculate nucleus: an ultrastructural study. Exp. Brain Res. *52*, 57–66.

Hamos, J.E., Van Horn, S.C., Raczkowski, D., and Sherman, S.M. (1987). Synaptic circuits involving an individual retinogeniculate axon in the cat. J. Comp. Neurol. *259*, 165–192.

Harting, J.K., Huerta, M.F., Hashikawa, T., and Van Lieshout, D.P. (1991). Projection of the mammalian superior colliculus upon the dorsal lateral geniculate nucleus: organization of tectogeniculate pathways in nineteen species. J. Comp. Neurol. *304*, 275–306.

Hayhow, W.R., Sefton, A., and Webb, C. (1962). Primary optic centers of the rat in relation to the terminal distribution of the crossed and uncrossed optic nerve fibers. J. Comp. Neurol. *118*, 295–322.

Heggelund, P. and Harveit, E. (1990). Neurotransmitter receptors mediating excitatory input to cells in the cat lateral geniculate nucleus. I. Lagged cells. J. Neurophysiol. *63*, 1347–1360.

Hickey, T.L. and Guillery, R.W. (1974). An autoradiographic study of retinogeniculate pathways in the cat and the fox. J. Comp. Neurol. *156*, 239–254.

Hirsch, J.C., Fourment, A., and Marc, M.E. (1983). Sleep-related variations of membrane potentials in the lateral geniculate body relay neurons of the cat. Brain Res. *259*, 308–312.

Hu, B., Steriade, M., and Deschenes, M. (1989a). The effects of brainstem peribrachial stimulation on perigeniculate neurons, the block of spindle waves. Neuroscience *31*, 1–12.

Hu, B., Steriade, M., and Deschenes, M. (1989b). The effects of brainstem peribrachial stimulation on neurons of the lateral geniculate nucleus. Neuroscience *31*, 13–24.

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. and Wiesel, T.N. (1961). Integrative action in the cat's lateral geniculate body. J. Physiol. *155*, 385–398.

Humphrey, A.L. and Weller, R.E. (1988a). Functionally distinct groups of X-cells in the lateral geniculate nucleus of the cat. J. Comp. Neurol. *268m*, 429–447.

Humphrey, A.L. and Weller, R.E. (1988b). Structural correlates of functional X-cells in the lateral geniculate nucleus of the cat. J. Comp. Neurol. *268*, 448–468.

Humphrey, A.L. and Saul, A.B. (2002). The Emergence of Direction Selectivity in Cat Primary Visual Cortex. B.R. Payne and A. Peters, eds. The cat primary visual cortex. (New York/Academic Press), pp. 343–386.

Ichida, J.M. and Casagrande, V.A. (2002). Organization of the feedback pathway from striate cortex (V1) to the lateral geniculate nucleus (LGN) in the owl monkey (*Aotus trivirgatus*). J. Comp. Neurol. *454*, 272–283.

Ichida, J.M., Ichida, J.M., Mavity-Hudson, J.A., and Casagrande, V.A. (2014). Distinct patterns of corticogeniculate feedback to different layers of the lateral geniculate nucleus. Eye Brain *6* (suppl 1), 57–73.

Illing, R.-B. and Wassle, H. (1981). The retinal projection to the thalamus in the cat: a quantitative investigation and comparison with the retinotectal pathway. J. Comp. Neurol. *202*, 265–285.

Jones, H.E., Andolina, I.M., Ahmed, B., Shipp, S.D., Clements, J.T.C., Grieve, K.L., Cudeiro, J., Salt, T.E., and Sillito, A.M. (2012). Differential feedback modulation of center and surround mechanisms in parvocellular cells in the visual thalamus. J. Neurosci. *32*, 15946–15951.

Kang, I. and Malpeli, J.G. (2009). Dim-light sensitivity of cells in the awake cat's lateral geniculate and medial interlaminar nuclei: a correlation with behavior. J. Neurophysiol. *102*, 841–852.

Kang, I., Reem, R.E., Kaczmarowski, A.L., and Malpeli, J.G. (2009). Contrast sensitivity of cats and humans in scotopic and mesopic conditions. J. Neurophysiol. *102*, 831–840.

Kaplan, E. and Shapley, R. (1984). The origin of the S (slow) potential in the mammalian lateral geniculate nucleus. Exp. Brain Res. *55*, 111–116.

Kaplan, E. and Shapley, R.M. (1986). The primate retina contains two types of ganglion cells, with high and low contrast sensitivity. Proc. Natl. Acad. Sci. USA *83*, 2755–2757.

Kaplan, E., Purpora, K., and Shapley, R.M. (1987). Contrast affects the transmission of visual information through the mammalian lateral geniculate nucleus. J. Physiol. *391*, 267–288.

Kara, P. and Reid, R.C. (2003). Efficacy of retinal spikes in driving cortical responses. J. Neurosci. *23*, 8547–8557.

Keat, J., Reinagel, P., Reid, R.C., and Meister, M. (2001). Predicting every spike: a model for the responses of visual neurons. Neuron *30*, 803–817.

Kosareva, A.A. (1980). Retinal projections in lamprey (*Lampetra fluviatilis*). J. Hirnforsch. *21*, 243–256.

Kratz, K.E., Webb, S.V., and Sherman, S.M. (1978). Studies of the cat's medial interlaminar nucleus: a subdivision of the dorsal lateral geniculate nucleus. J. Comp. Neurol. *181*, 601–614.

Kwon, Y.H., Esguerra, M., and Sura, M. (1991). NMDA and non-NMDA receptors mediate visual responses of neurons in the cat's lateral geniculate nucleus. J. Neurophysiol. *66*, 414–428.

Lal, R. and Friedlander, M.J. (1989). Gating of retinal transmission by afferent eye position and movement signals. Science *243*, 93–96.

Lal, R. and Friedlander, M.J. (1990). Effects of passive eye movement on retinogeniculate transmission in the cat. J. Neurophysiol. *63*, 523–538.

Lee, D. and Malpeli, J.G. (1998). Effects of saccades on the activity of neurons in the cat lateral geniculate nucleus. J. Neurophysiol. *79*, 922–936.

Lee, B.B., Virsu, V., and Creutzfeldt, O.D. (1983). Linear signal transmission from prepotentials to cells in the macaque lateral geniculate nucleus. Exp. Brain Res. *52*, 50–56.

Lee, C., Malpeli, J.G., Schwark, H.D., and Weyand, T.G. (1984). Cat medial interlaminar nucleus: retinopy, relation to tapetum and implications for scotopic vision. J. Neurophysiol. *52*, 848–869.

Lee, D., Lee, C., and Malpeli, J.G. (1992). Acuity-sensitivity trade-offs of X and Y cells in the cat lateral geniculate complex: role of the medial interlaminar nucleus in scotopic vision. J. Neurophysiol. *68*, 1235–1247.

Levick, W.R., Cleland, B.G., and Dubin, M.W. (1972). Lateral geniculate neurons of cat: retinal inputs and physiology. Invest. Ophthalmol. *11*, 302–311.

Levine, M.W. and Cleland, B.G. (2001). An analysis of the effect of retinal ganglion impulses upon the firing probability of neurons in the dorsal lateral geniculate nucleus of the cat. Brain Res. *902*, 244–254.

Lindstrom, S. (1982). Synaptic organization of inhibitory pathways to principal cells in the lateral geniculate nucleus of the cat. Brain Res. *234*, 447–453.

Lindstrom, S. and Wrobel, A. (2011). Feedforward and recurrent inhibitory receptive fields of principal cells in the cat's dorsal lateral geniculate nucleus. Pflüger's Arch. Eur. J. Physiol. *461*, 277–294.

Liu, R.C., Tzonev, S., Rebrik, S., and Miller, K.D. (2001). Variability and information in a neural code of the cat lateral geniculate nucleus. J. Neurophysiol. *86*, 2789–2806.

Livingstone, M.S. and Hubel, D.H. (1981). Effects of sleep and arousal on the processing of visual information in the cat. Nature *291*, 554–561.

Llinas, R. and Jahnsen, H. (1982). Electrophysiology of mammalian thalamic neurones *in vitro*. Nature *297*, 406–408.

Lo, F.-S. (1981). Synaptic organization of the lateral geniculate nucleus of the rabbit: lack of feedforward inhibition. Brain Res. *221*, 387–392.

Lo, F.-S. (1988). A study of neuronal circuitry mediating the saccadic suppression in the rabbit. Exp. Brain Res. *71*, 618–622.

Lu, S.-M., Guido, W., and Sherman, S.M. (1992). Effects of membrane voltage on receptive field properties of lateral geniculate neurons in the cat: contributions of the low threshold Ca^{2+} conductance. J. Neurophysiol. *68*, 2185–2198.

Lund, J.S., Lund, R.D., Hendrickson, A.E., Bunt, A.H., and Fuchs, A.F. (1975). The origin of efferent pathways from the primary visual cortex, area 17, of the macaque monkey. J. Comp. Neurol. *164*, 287–304.

Macknik, S.L. and Martinez-Conde, S. (2004a). Dichoptic visual masking reveals that early binocular neurons exhibit weak interocular suppression: implications for binocular vision and visual awareness. J. Cogn. Neurosci. *16*, 1–11.

Macknik, S.L. and Martinez-Conde, S. (2004b). The spatial and temporal effects of lateral inhibitory networks and their relevance to the visibility of spatiotemporal edges. Neurocomputing *58–60C*, 775–782.

Macknik, S.L. and Martinez-Conde, S. (2009). The Role of Feedback in Visual Attention and Awareness. M.S. Gazzaniga, ed. The Cognitive Neurosciences. (Cambridge, MA/MIT Press), pp. 1165–1180.

Macknik, S.L., Martinez-Conde, S., and Haglund, M.M. (2000). The role of spatiotemporal edges in visibility and visual masking. Proc. Natl. Acad. Sci. USA *97*, 7556–7560.

Mante, V., Frazor, R.A., Bonin, V., Geisler, W.S., and Carandini, M. (2005). Independence of luminance and contrast in natural scenes in the early visual system. Nat. Neurosci. *8*, 1690–1697.

Mante, V., Bonin, V., and Carandini, M. (2008). Functional mechanisms shaping lateral geniculate responses to artificial and natural stimuli. Neuron *58*, 625–638.

Martinez, L.M., Molano-Mazon, M., Wang, X., Sommer, F.T., and Hirsch, J.A. (2014). Statistical wiring of thalmic receptive fields optimizes spatial sampling of the retinal image. Neuron *81*, 943–956.

Martinez-Conde, S., Macknik, S.L., and Hubel, D.H. (2002). The function of bursts of spikes during visual fixation in the awake primate lateral geniculate nucleus and primary visual cortex. Proc. Natl. Acad. Sci. USA *99*, 13920–13925.

Martinez-Conde, S., Macknik, S.L., and Hubel, D.H. (2004). The role of fixational eye movement in visual perception. Nat. Rev. Neurosci. *5*, 229–240.

Martinez-Conde, S., Macknik, S.L., Troncoso, X.G., and Dyar, T.A. (2006). Microsaccades counteract visual fading during fixation during fixation. Neuron *49*, 297–305.

Martinez-Conde, S., Otero-Millan, J., and Macknik, S.L. (2013). The impact of microsaccades on vision: towards a unified theory of saccadic function. Nat. Rev. Neurosci. *14*, 83–96.

Mastronarde, D.N. (1987a). Two classes of single-input X-cells in cat lateral geniculate nucleus. I. Receptive-field properties and classification of cells. J. Neurophysiol. *57*, 357–380.

Mastronarde, D.N. (1987b). Two classes of single-input x-cells in cat lateral geniculate nucleus. II. Retinal inputs and the generation of receptive field properties. J. Neurophysiol. *57*, 381–413.

Mastronarde, D.N. (1992). Nonlagged relay cells and interneurons in the cat lateral geniculate nucleus: receptive field properties and retinal inputs. Visual Neurosci. *8*, 407–441.

Maunsell, J.H., Ghose, G.M., Assad, J.A., McAdams, C.J., Boudreau, C.E., and Noerager, B.D. (1999). Visual response latencies of magnocellular and parvocellular LGN neurons in macaque monkeys. Visual Neurosci. *16*, 1–14.

McAlonan, K., Cavanaugh, J., and Wurtz, R.H. (2008). Guarding the gateway to cortex with attention in visual thalamus. Nature *456*, 391–395.

McCamy, M.B., Otero-Millan, J., Di Stasi, L.L., Macknik, S.L., and Martinez-Conde, S. (2014). Highly informative natural scene regions increase microsaccade production during visual scanning. J. Neurosci. *34*, 2956–2966.

McCarley, R.W., Benoit, O., and Barrionuevo, G. (1983). Lateral geniculate nucleus unitary discharge in sleep and waking, state- and rate-specific aspects. J. Neurophyiol. *50*, 798–818.

McClurkin, J.W., Gawne, T.J., Richmond, B.J., Optican, L.M., and Robinson, D.L. (1991a). Lateral geniculate neurons in behaving primates I. Responses to two-dimensional stimuli. J. Neurophysiol. *66*, 777–793.

McClurkin, J.W., Gawne, T.J., Optican, L.M., and Richmond, B.J. (1991b). Lateral geniculate neurons in behaving primates. II. Encoding of visual information in the temporal shape of the response. J. Neurophysiol. *66*, 794–808.

McCormick, D.A. (1989). Cholinergic and noradrenergic modulation of thalamocortical processing. Trends Neurosci. *6*, 215–221.

McCormick, D.A. and Bal, T. (1997). Sleep and arousal: thalamocortical mechanisms. Annu. Rev. Neurosci. *20*, 185–215.

McCormick, D.A. and Pape, H.-C. (1988). Acetylcholine inhibits identified interneurons in the in the cat lateral geniculate nucleus. Nature *334*, 246–248.

McCormick, D.A. and Prince, D.A. (1987). Actions of acetylcholine in the guinea-pig and cat medial and lateral geniculate nuclei, *in vitro*. J. Physiol. *392*, 147–165.

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

Michael, C.R. (1988). Retinal afferent arborization patterns, dendritic field orientations, and segregation of function in the lateral geniculate nucleus of the monkey. Proc. Natl. Acad. Sci. USA *85*, 4914–4918.

Montero, V.M. and Zempel, J. (1986). The proportion and size of GABA-immunoreactive neurons in the magnocellular and parvocellular layers of the lateral geniculate nucleus of the rhesus monkey. Exp. Brain Res. *62*, 215–223.

Moruzzi, G. and Magoun, H.W. (1949). Brain stem reticular formation and activation of the EEG. Electroencephalogr. Clin. Neurophysiol. *1*, 455–473.

Murphy, P.C. and Sillito, A.M. (1996). Functional morphology of the feedback pathway from area 17 of the cat visual cortex o the lateral geniculate nucleus. J. Neurosci. *16*, 1180–1192.

Murthy, A. and Humphrey, A.L. (1999). Inhibitory contributions to spatiotemporal receptive field structure and direction selectivity in simple cells of cat area 17. J. Neurophysiol. *81*, 1212–1224.

Nassi, J.J. and Callaway, E.M. (2009). Parallel processing strategies of the primate visual system. Nat. Rev. Neurosci. *10*, 360–372.

O'Conner, D.H., Fukui, M.M., Pinsk, M.A., and Kastner, S. (2002). Attention modulates responses in the human lateral geniculate nucleus. Nat. Neurosci. *5*, 1203–1209.

Olshausen, B.A. and Field, D.H. (2004). Sparse coding of sensory inputs. Curr. Opin. Neurobiol. *14*, 481–487.

Olveczky, B.P., Baccus, S.A., and Meister, M. (2003). Segregation of object and background motion in the retina. Nature *423*, 401–408.

Peichl, L. and Wassle, H. (1979). Size, scatter and coverage of ganglion cell receptive fields in the cat retina. J. Physiol. *291*, 117–141.

Perry, V.H., Oehler, R., and Cowey, A. (1984). Retinal ganglion cells that project to the dorsal lateral geniculate nucleus in the macaque monkey. Neuroscience *12*, 1101–1123.

Pitkow, X. and Meister, M. (2012). Decorrelation and efficient coding by retinal ganglion cells. Nat. Neurosci. *15*, 628–635.

Ramcharan, E.J., Gnadt, J.W., and Sherman, S.M. (2000). Burst and tonic firing in thalamic cells of unanesthetized, behaving monkeys. Vis. Neurosci. *17*, 55–62.

Ramcharan, E.J., Gnadt, J.W., and Sherman, S.M. (2005). Higher-order thalamic relays burst more than first-order relays. Proc. Natl. Acad. Sci. USA *102*, 12236–12241.

Rathbun, D.L., Warland, D.K., and Usrey, W.M. (2010). Spike timing and information transmission at retinogeniculate synapses. J. Neurosci. *30*, 13558–13566.

Reid, R.C., Victor, J.D., and Shapley, R.M. (1997). The use of m-sequences in the analysis of visual neurons: linear receptive field properties. Visual Neurosci. *14*, 1015–1027.

Reppas, J.B., Usrey, W.M., and Reid, R.C. (2002). Saccadic eye movements modulate visual responses in the lateral geniculate nucleus. Neuron *35*, 961–974.

Ringach, D.L. (2004). Mapping receptive fields in primary visual cortex. J. Physiol. *558*, 717–728.

Rioch, D.M. (1929). Studies of the diencephalon of carnivore. I. The nuclear configuration of the thalamus, epithalamus and hypothalamus of the dog and cat. J. Comp. Neurol. *49*, 1–118.

Robson, J.A. (1984). Reconstructions of corticogeniculate axons in the cat. J. Comp. Neurol. *225*, 193–200.

Robson, J.A. (1993). Qualitative and quantitative analyses of the patterns of retinal input to neurons in the dorsal lateral geniculate nucleus of the cat. J. Comp. Neurol. *334*, 324–336.

Roska, B. and Werblin, F. (2003). Rapid global shifts in natural scenes block spiking in specific ganglion cell types. Nat. Neurosci. *6*, 600–608.

Rowe, M.H. and Fischer, Q. (2001). Dynamic properties of retinogeniculate synapses in the cat. Vis. Neurosci. *18*, 219–231.

Royal, D.W., Gy, S., Schall, J.D., and Casagrande, V.A. (2006). Correlates of motor planning and postsaccadic fixation in the macaque monkey lateral geniculate nucleus. Exp. Brain Res. *168*, 62–75.

Rucci, M. and Victor, J.D. (2015). The unsteady eye: an information-processing stage, not a bug. Trends Neurosci. *38*, 195–206.

Rucci, M., Iovin, R., Poletti, M., and Santini, F. (2007). Miniature eye movements enhance fine spatial detail. Nature *447*, 851–854.

Ruiz, O., Royal, D., Sary, G., Chen, X., Schall, J.D., and Casagrande, V.A. (2006). Low-threshold Ca^{2+} associated bursts are rare events in the LGN of the awake, behaving monkey. J. Neurophysiol. *95*, 3401–3413.

Sakakura, H. (1968). Spontaneous and evoked unitary activities of cat lateral geniculate neurons in sleep and wakefulness. Jpn. J. Physiol. *18*, 23–42.

Saul, A.B. (2008). Lagged cells. Neurosignals *16*, 209–225.

Saul, A.B. (2009). Lagged cells in alert monkey lateral geniculate nucleus. Vis. Neurosci. *25*, 647–659.

Saul, A.B. and Humphrey, A.L. (1990). Spatial and temporal response properties of lagged and nonlagged cells in the cat lateral geniculate nucleus. J. Neurophysiol. *64*, 206–224.

Saul, A.B. and Humphrey, A.L. (1992). Evidence of input from lagged cells in the lateral geniculate nucleus to simple cells in cortical area 17 of the cat. J. Neurophysiol. *68*, 1190–1208.

Sawai, H., Morigiwa, K., and Fukuda, Y. (1988). Effects of EEG synchronization on visual responses of cat's geniculate relay cells: a comparison among Y, X and W cells. Brain Res. *455*, 394–400.

Schein, S.J. and de Monasterio, F.M. (1987). Mapping of retinal and geniculate neurons onto striate cortex of macaque. J. Neurosci. *7*, 996–1009.

Schiller, P.H. and Malpeli, J.G. (1977). Properties and tectal projections of monkey retinal ganglion cells. J. Neurophysiol. *40*, 428–445.

Schiller, P.H. and Malpeli, J.G. (1978). Functional specificity of lateral geniculate laminae of the rhesus monkey. J. Neurophysiol. *41*, 788–797.

Schmidt, M. (1996). Neurons in the cat pretectum that project to the dorsal lateral geniculate nucleus are activated during saccades. J. Neurophysiol. *76*, 2907–2918.

Sestokas, A.K. and Lehmkuhle, S. (1988). Response variability of X- and Y-cells in the dorsal lateral nucleus of the cat. J. Neurophysiol. *59*, 317–325.

Sherman, S.M. (2001). Tonic and burst firing: dual modes of thalamocortical relay. Trends Neurosci. *24*, 122–127.

Sherman, S.M. (2004). Interneurons and triadic circuitry of the thalamus. Trends Neurosci. *27*, 670–675.

Sherman, S.M. and Guillery, R.W. (1996). Functional organization of thalamocortical relays. J. Neurophysiol. *76*, 1367–1396.

Sherman, S.M. and Guillery, R.W. (2004). Thalamus. G.M. Shepard, ed. Synaptic Organization of Brain. (New York/Oxford U Press).

Sherman, S.M. and Koch, C. (1986). The control of retinogeniculate transmission in the mammalian lateral geniculate nucleus. Exp. Brain Res. *63*, 1–20.

Sillito, A.M., Cudeiro, J., and Murphy, P.C. (1993). Orientation sensitive elements in the corticofugal influence on center-surround interactions in the dorsal lateral geniculate nucleus. Exp. Brain Res. *93*, 6–16.

Sillito, A.M., Cudeiro, J., and Jones, H.E. (2006). Always returning: feedback and sensory processing in visual cortex and thalamus. Trends Neurosci. *29*, 307–316.

Simoncelli, E.P. and Olshausen, B.A. (2001). Natural image statistics and neural representation. Annu. Rev. Neurosci. *24*, 1193–1216.

Sincich, L.C., Adams, D.L., Economides, J.R., and Horton, J.C. (2007). Transmission of spike trains at the retinogeniculate synapse. J. Neurosci. *27*, 2683–2692.

Sincich, L.C., Horton, J.C., and Sharpee, T.O. (2009). Preserving information in neural transmission. J. Neurosci. *29*, 6207–6216.

Singer, W. (1977). Control of thalamic transmission by corticofugal and ascending reticular pathways in the visual system. Physiol. Rev. *57*, 386–420.

Singer, W., Poppel, E., and Creutzfeldt, O.D. (1972). Inhibitory interaction in the cat's lateral geniculate nucleus. Exp. Brain Res. *14*, 210–226.

Solomon, S.G., Tailby, C., Cheong, S.K., and Camp, A.J. (2010). Linear and nonlinear contributions to the visual sensitivity of

neurons in primate lateral geniculate nucleus. J. Neurophysiol. *104*, 1884–1898.

Spear, P.D., Kim, C.B.Y., Ahmad, A., and Tom, B.W. (1996). Relationship between numbers of retinal ganglion cells and lateral geniculate neurons in the rhesus monkey. Visual Neurosci. *13*, 199–203.

Stanford, L.R. (1987). W-cells in the cat retina: correlated morphological and physiological evidence for two distinct classes. J. Neurophysiol. *57*, 218–244.

Stanley, G.B., Li, F.F., and Dan, Y. (1999). Reconstruction of natural scenes from ensemble responses in the lateral geniculate nucleus. J. Neurosci. *19*, 8036–8042.

Strong, S.P., Koberle, R., de Ruyter van Steveninck, R.R., and Bialek, W. (1998). Entropy and information in neural spike trains. Physical Rev. Lett. *80*, 197–200.

Sur, M., Esguerra, M., Garraghty, P.E., Kritzer, M.F., and Sherman, S.M. (1987). Morphology of physiologically identified X- and Y-axons in the cat. J. Neurophysiol. *58*, 1–32.

Swadlow, H.A. and Gusev, A.G. (2001). The impact of 'bursting' thalamic impulses at a neocortical synapse. Nat. Neurosci. *4*, 402–408.

Swadlow, H.A. and Weyand, T.G. (1985). Receptive field and axonal properties of neurons in the dorsal lateral geniculate nucleus of awake, unparalyzed rabbits. J. Neurophysiol. *54*, 168–183.

Swadlow, H.A. and Weyand, T.G. (1987). Corticogeniculate neurons, corticotectal neurons, and suspected interneurons in visual cortex of awake rabbits: receptive-field properties, axonal properties, and effects of EEG arousal. J. Neurophysiol. *57*, 977–1001.

Szentagothai, J. (1963). The structure of the synapse in the lateral geniculate nucleus. Acta Anat. *55*, 166–185.

Theunissen, F.E., Sen, K., and Doupe, A.J. (2000). Sprectral-temporal receptive fields of nonlinear auditory neurons obtained using natural sounds. J. Neurosci. *20*, 2315–2331.

Theunissen, F.E., David, S.V., Singh, N.C., Hsu, A., Vinje, W.E., and Gallant, J.L. (2001). Estimating spatio-temporal receptive fields from their responses to natural stimuli. Network: Comput. Neural Syst. *12*, 289–316.

Thuma, B.D. (1928). Studies of the diencephalon of the cat. I. The cyto-architecture of the corpus geniculatum laterale. J. Comp. Neurol. *46*, 173–199.

Tsumoto, T. and Suda, K. (1980). Three groups of cortico-geniculate neurons and their distribution in binocular and monocular segments of cat striate cortex. J. Comp. Neurol. *193*, 223–236.

Turner, J.P. and Salt, T.E. (1998). Characterization of sensory and corticothalamic excitatory inputs to rat thalamocortical neurones *in vitro*. J. Physiol. *510*, 829–843.

Turvey, M.T. (1979). The thesis of the efference-mediation of vision cannot be rationalized. Behav. Brain Sci. *2*, 81–83.

Uglesich, R., Casti, A., Hayot, F., and Kaplan, E. (2009). Stimulus size dependence of information transfer from retina to thalamus. Front. Syst. Neurosci. *3*, 1–9.

Usrey, W.M., Reppas, J.B., and Reid, R.C. (1998). Paired-spike interactions and synaptic efficacy of retinal inputs to the thalamus. Nature *395*, 384–387.

Usrey, W.M., Reppas, J.B., and Reid, R.C. (1999). Specificity and strength of retinogeniculate connections. J. Neurophysiol. *82*, 3527–3540.

Usrey, W.M., Alonso, J.M., and Reid, R.C. (2000). Synaptic interactions between thalamic inputs to simple cells in cat visual cortex. J. Neurosci. *20*, 5461–5467.

Van Hooser, S.D., Heimel, A.F., and Nelson, S.B. (2003). Receptive field properties and laminar organization of lateral geniculate nucleus in the gray squirrel (*Sciurus carolinensis*). J. Neurophysiol. *90*, 3398–3418.

Van Hooser, S.D., Roy, A., Rhodes, H.J., Culp, J.H., and Fitzpatrick, D. (2013). Transformation of receptive field properties from lateral geniculate nucleus to superficial V1 in the tree shrew. J. Neurosci. *33*, 11494–11505.

Van Horn, S., Erisir, A., and Sherman, S.M. (2000). Relative distribution of synapses in the A-laminae of the lateral geniculate nucleus of the cat. J. Comp. Neurol. *415*, 509–520.

Vigeland, L.E., Contreras, D., and Palmer, L.A. (2013). Synaptic mechanisms of temporal diversity in the lateral geniculate nucleus of the thalamus. J. Neurosci. *33*, 1887–1896.

Vinje, W.E. and Gallant, J.L. (2002). Natural stimulation of the non-classical receptive field increases information transmission efficiency in V1. J. Neurosci. *22*, 2904–2915.

Wang, C., Cleland, B.G., and Burke, W. (1985). Synaptic delay in the lateral geniculate nucleus of the cat. Brain Res. *343*, 236–245.

Wang, X., Wei, Y., Vaingankar, V., Wang, Q., Koepsell, K., Sommer, F.T., and Hirsch, J.A. (2007). Feedforward excitation and inhibition evoke dual modes of firing in the cat's visual thalamus during naturalistic viewing. Neuron *55*, 465–478.

Wang, H.-P., Spencer, D., Fellous, J.-M., and Sejnowski, T.J. (2010). Synchrony of thalamocortical inputs maximizes cortical reliability. Science *328*, 106–109.

Wang, X., Vaingankar, V., Sanchez, C.S., Sommer, F.T., and Hirsch, J.A. (2011). Thalamic interneurons and relay cells use complementary synaptic mechanisms for visual processing. Nat. Neurosci. *14*, 224–231.

Wassle, H., Peichl, L., and Boycott, B.B. (1981a). Morphology and topography of on- and off-alpha cells in the cat retina. Proc. R. Soc. Lond. B Biol. Sci. *212*, 157–175.

Wassle, H., Boycott, B., and Illing, R. (1981b). Morphology and mosaic of on-and off-cells in cat retina and some functional considerations. Proc. R. Soc. Lond. B Biol. Sci. *212*, 177–195.

Watson, A.B. and Ahumada, A.J. (1985). Model of human visual-motion sensing. J. Opt. Soc. Am. A *2*, 322–341.

Weyand, T.G. (2007). Retinogeniculate transmission in wakefulness. J. Neurophysiol. *98*, 769–785.

Weyand, T.G. and Malpeli, J.G. (1993). Response of neurons in primary visual cortex are modulated by eye position. J. Neurophysiol. *69*, 2258–2260.

Weyand, T.G., Boudreaux, M., and Guido, W. (2001). Burst and tonic response modes in thalamic neurons during sleep and wakefulness. J. Neurophysiol. *85*, 1107–1118.

Wilson, J.R. (1989). Synaptic organization of individual neurons in the macaque lateral geniculate nucleus. J. Neurosci. *9*, 2931–2953.

Wolfe, J. and Palmer, L.A. (1998). Temporal diversity in the lateral geniculate nucleus of the cat. Vis. Neurosci. *15*, 653–673.

Yeh, C.-I., Stoelzel, C.R., Weng, C., and Alonso, J.-M. (2009). Functional consequences of neuronal divergence within the retinogeniculate pathway. J. Neurophysiol. *101*, 2166–2185.