Visual Neuroscience (2001), **18**, 253–258. Printed in the USA.

The effects of saccadic eye movements on the activity of geniculate relay neurons in the monkey

E.J. RAMCHARAN, J.W. GNADT, AND S.M. SHERMAN

Department of Neurobiology, State University of New York, Stony Brook

(RECEIVED October 4, 2000; ACCEPTED November 30, 2000)

Abstract

Saccadic suppression is the reduced visibility that occurs during saccadic eye movements. Recent psychophysical studies have suggested that this is due to a reduction in responsiveness of magnocellular (M), but not parvocellular (P), cells of the lateral geniculate nucleus. To address this and other phenomena of responsiveness during saccades, we recorded from geniculate neurons in the behaving monkey before, during, and after saccades. Specifically, we measured neuronal responses to a flashing, whole-field illumination. Contrary to the prediction, most M neurons showed pronounced *enhancement* of visual activity during saccades, whereas such responsiveness of parvocellular (P) neurons was not significantly affected by saccades. We also analyzed the extent to which saccades affected burst firing, which results from activation of a voltage-dependent Ca^{2+} conductance. We found that both M and P cells displayed a significant suppression of burst firing during saccades. These results do not support the idea that saccadic suppression has an obvious substrate in reduced responsiveness of geniculate cells, but this suppression may be related to an increased visual threshold for detection associated with reduced burst firing.

Keywords: Burst, Eye movement, Lateral geniculate nucleus, Vision, Low-threshold spike

Introduction

Normal vision is continuously being interrupted by saccadic eye movements made from one point in the visual field to another. During these rapid movements, which are made to foveate images, the visual world is swept across the retina and might be expected to produce blurred vision for periods of up to about 100 ms depending on the size of the saccade (Robinson, 1964). However, our perception remains relatively stable during these events due to a phenomenon known as saccadic suppression, which dramatically reduces visual sensitivity during saccades. How saccadic suppression is achieved is unknown, but mechanisms such as central suppression of visual transmission (Holt, 1903) and visual masking (MacKay, 1970; Campbell & Wurtz, 1978) have been proposed. More recent psychophysical studies have suggested that the form and motion part of the visual system, presumed to involve the magnocellular (M) pathway, is selectively suppressed at an early stage presumed to be at the level of the lateral geniculate nucleus (LGN) (Burr et al., 1994; Diamond et al., 2000). By this notion, the parallel parvocellular (P) pathway is relatively unaffected by saccades. There are numerous nonretinal, modulatory inputs to the lateral geniculate nucleus that could be involved in controlling suppression of retinogeniculate transmission (reviewed in Sherman & Guillery, 1996), and it is plausible that this could be selectively gated for the M and P pathways. There is accumulating evidence that these high-velocity eye movements modulate the visual activity of geniculate relay neurons in cat (Noda, 1975; Fischer et al., 1996), rabbit (Lo, 1988; Zhu & Lo, 1996), and monkey (Büttner & Fuchs 1973; Bartlett et al., 1976; Wilson & Noyd, 1998; Reppas et al., 1999). However, there is no consensus as to the nature of the modulatory effects of saccades on the responsiveness of different types of relay neurons.

Furthermore, thalamic relay cells are known to fire in two very different response modes that affect the nature of retinogeniculate transmission (Sherman, 1996; Sherman & Guillery, 1996): these are the *tonic* and *burst* modes, which depend on the inactivation state of a voltage-dependent Ca^{2+} conductance. Activation of this conductance, which can be accomplished from relatively hyperpolarized levels at which the Ca^{2+} conductance is deinactivated, leads to the influx of Ca^{2+} resulting in the production of a low-threshold spike (LTS) and burst firing. If instead the cell is relatively depolarized, which would inactivate the Ca^{2+} conductance, an activating input will not trigger an LTS and will produce a steady stream of unitary action potentials representing tonic firing. Behaviorally, burst firing occurs most frequently during slow wave sleep (Steriade et al., 1993), but it also occurs occasionally in the fully awake animal (McCarley et al., 1983; Guido & Weyand, 1995; Ramcharan et al., 2000*a*). During the relay of visual information, tonic firing is thought to produce a more accurate faithful, linear relay of sensory information to the cortex, whereas burst firing may result in better signal detection (reviewed in Sherman, 1996).

We therefore sought to determine how saccades might affect the overall responsiveness of geniculate neurons in the behaving monkey as well as the burst or tonic firing mode of these cells.

Address correspondence and reprint requests to: E.J. Ramcharan, Department of Neurobiology, State University of New York, Stony Brook, NY 11794-5230, USA. E-mail: eramcharan@notes.cc.sunysb.edu

Methods

We made single-unit recordings in two Rhesus monkeys that were treated in accordance with institutional guidelines for animal care. The animals used in this study were not sacrificed. We have previously described the general techniques (Ramcharan et al., 2000*a*) and briefly outline them here. Recording cylinders and scleral eye coils were surgically placed on the animals. All recordings were made while the animal sat in a confinement chair. These chairs were customized for each animal so as to maximize their comfort during training and recording sessions, each typically lasting for about 2 h. To motivate the subjects, the daily intake of water was restricted to that earned as reward for successful completion of trials. After several weeks of training, monkeys were able to fixate a small visual target contained within an error window (a square 2.5 deg per side) and make saccades to the target after it jumped to a new position. A single trial consisted of a variable fixation period, then a 10-deg horizontal rightward saccade to the new target position, then a fixation on this new position for a variable period, then a saccade back to the original point, and then a final fixation period. The fixation periods before saccades varied randomly between 750 and 2000 ms before the target jumped to a new position. Each trial therefore consisted of two saccadic eye movements. Both forward and return saccades were pooled together for data analysis since there was no difference in activity between the two directions.

Insulated tungsten electrodes were lowered through the dura into the thalamus. Neurons in the lateral geniculate nucleus were identified by their relatively small visual receptive fields, predictable ocular dominance switching as we progressed through the laminae, and a change to larger receptive fields with better contrast sensitivity as we passed from P to M laminae. We measured responses evoked during square-wave flashing at 8 Hz of a 25 deg by 20 deg region adjusted so that the receptive field always fell within the screen during all phases of fixation and saccade periods. The flashing stimulus was constantly present during the totality of each trial. We used a square-wave stimulus at a temporal frequency of 8 Hz and zero spatial frequency (Cambridge Systems VSG 2/3 graphics card) because this is the highest temporal frequency we found to satisfactorily drive neurons while maximizing the chances of stimuli occurring during the relatively short time span of the eye movement.

All resulting neuronal action potentials were monitored on an oscilloscope and single-unit activity was isolated through a time/amplitude window discriminator and recorded by a computer with a sampling period of 0.1 ms. Eye position was monitored using the scleral eye coil technique with a resolution of 2 ms temporally and 0.2 deg spatially.

All statistics were done using Repeated Measures ANOVA with Tukey-Kramer Multiple Comparisons test (GraphPad Instat, GraphPad Software, San Diego, CA).

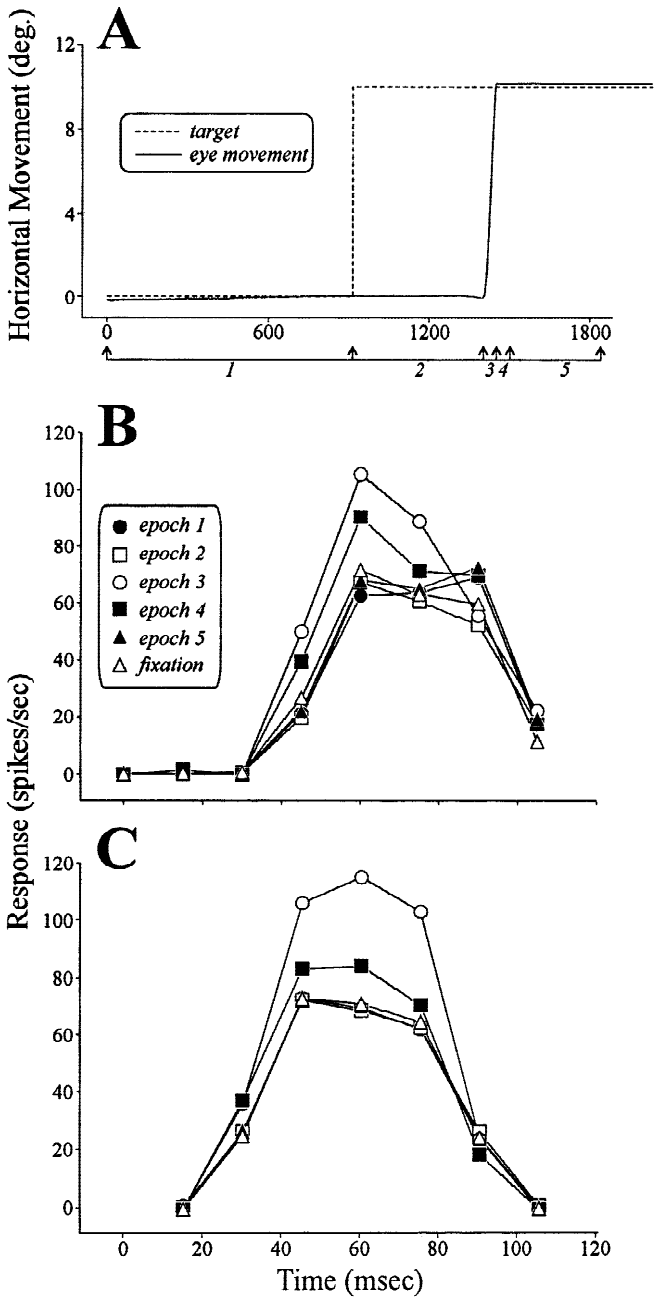

Fig. 1. Schematic of saccadic eye movement (A) plus responses of two magnocellular cells (B and C) to a full-field 8-Hz flashing stimulus. Below the schematic are shown the 5 *epochs* described more fully in the text, with arrows indicating boundaries between *epochs*. Analysis to a cycle of the stimulus. Each line on the graphs of B and C represents averaged histograms for stimulus onsets during each of the *epochs*.

Results

We recorded from 21 relay neurons of the monkey lateral geniculate nucleus before, during, and after saccadic eye movements. These included ten magnocellular (M) and 11 parvocellular (P) neurons.

For analysis, each saccade trial was divided into five epochs, and the responses during each epoch was separately analyzed (see Fig. 1A). *Epoch 1* extends from the beginning of the fixation on the target to the time when the target jumps 10 deg horizontally to the right; *epoch 2* extends from this point to the beginning of the eye movement; *epoch 3* extends for the duration of the saccade; *epoch 4* consists of a 50-ms period after termination of the saccade; and *epoch 5* is the period from 50 ms following termination of the saccade to 300 ms. *Epochs 2–4* can be considered to be saccade related, with the latter two *epochs* representing the saccade proper. *Epoch 4* is included with the saccade, because responses of geniculate cells show visual latencies of ~50 ms, and thus any responses in *epoch 4* are likely to be evoked by stimuli

during the saccade. A final control consists of trials of fixation only during which the target did not jump and thus no saccades were generated. Responses during these five epochs plus the control (fixation-only) period were analyzed. We reasoned that the baseline response properties of the neurons should be similar during *epochs 1* and *5* and also during the fixation-only controls. The cell responses per stimulus cycle were sorted into epochs according to within which epoch the onset of the excitatory phase landed. ON-center cells responded to the bright phase of each cycle, and OFF-center cells to each dark phase. To simplify comparisons, we started each histogram with the excitatory phase of the stimulus (i.e. the bright cycle for ON-center cells and the dark cycle for OFF-center cells).

Responses for all ten M cells during simple fixation, involving *epochs 1, 2, 5*, and the fixation-only control, were indistinguishable. This indicates that there was no obvious response change in *epoch 2* (i.e. the period between target movement and the beginning of the saccade). Five of the ten M cells also showed no significant response changes during the saccade itself or the period immediately afterwards (*epochs 3* and *4*). However, the other five did show significant response elevation during one or both of these *epochs*. For two of these five neurons, the facilitation was significant only during *epoch 3* compared to the fixation periods ($P < 0.01$). Figs. 1B and 1C show the responses of these two cells. In these cases, it appears the facilitation peaked during the saccade (*epoch 3*) and tailed off in the 50-ms period after the saccade (*epoch 4*). For two others, the enhanced activity was significant in *epoch 4*, the period 50 ms after the eye movement ($P < 0.01$). Here it seems the enhancement in visual activity began during the eye movement and peaked during the 50 ms after. A fifth cell exhibited an increase in activity 50 ms after the saccade compared to the saccade ($P < 0.001$) and during periods of no eye movements ($P < 0.05$). In this case, there was a small insignificant saccadic suppression followed by a large significant postsaccadic facilitation. Of the remaining five cells that did not show any significant changes between the various episodes, three showed some small tendency towards enhanced visual activity during the saccade and extending to the earlier period after the saccade. The activity during saccades and the short period after saccades was also enhanced compared to the activity during fixation tasks. These findings are in agreement with Reppas et al. (1999) who reported that monkey geniculate magnocellular neurons exhibited saccadic related facilitation. We found no difference in the visual responsiveness between ON and OFF magnocellular neurons.

To illustrate the population behavior of the M neurons, the activity of each cell was normalized to its highest firing rate during any of the *epochs* or fixation only, and we averaged across these normalized values. The results are shown in Fig. 2A. These cells showed significant response enhancement during the saccadic eye movement (*epoch 3*) that lasted for at least 50 ms after the saccade (*epoch 4*; $P < 0.01$). During fixation (*epochs 1, 2*, and *5*), there was no difference in responsiveness from the fixation-only control.

In contrast to the effects on M cells, saccades had no discernable affect on the responsiveness to the visual stimuli for P cells (Figs. 2B and 3). None of the 11 P cells showed any significant changes among the various *epochs*, nor were any of these significantly different from the fixation-only control ($P > 0.1$ for all comparisons). Thus, we found no evidence for saccadic suppression among the 11 P cells as had previously been reported (Wilson & Noyd, 1998).

We also investigated the possibility that saccades affect the response mode—burst or tonic (see Introduction)—of geniculate

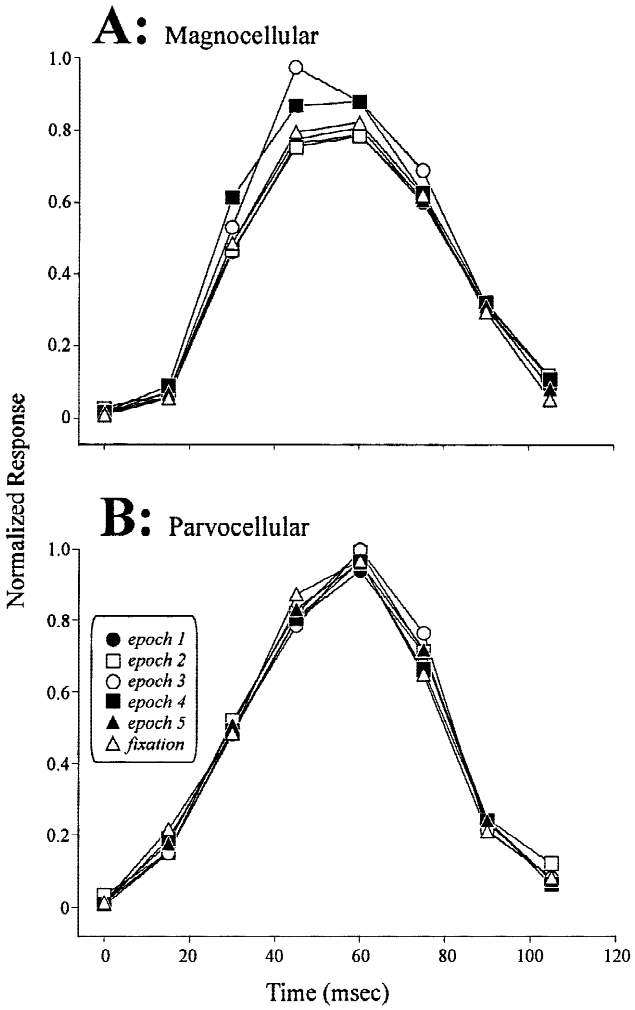

Fig. 2. Population analysis for responses to visual stimulation for magnocellular (A; $n = 10$) cells and parvocellular (B; $n = 11$) cells. Each response during each *epoch* has been normalized for comparison (see text for details).

neurons. As we have reported previously (Ramcharan et al., 2000*a*,*b*), bursting does occasionally occur in geniculate relay cells of the awake monkey under our behavioral conditions. In these experiments, the response to the majority of cycles of the visual response was in tonic mode, but bursts were occasionally seen. The extent of bursting varied considerably among cells (see Ramcharan et al., 2000*a*). On the whole the incidence of bursts varied anyway between one every 25 cycles of the stimulus to one every 250 cycles of the stimulus. We did not include possible bursts consisting of only one spike (see Ramcharan et al., 2000*a*,*b*). For this reason, we separated the eye movement trial into three episodes. We simplified this analysis by using only three sampling periods: *Before* started at the beginning of fixation and ran until the target moved (equivalent to *epoch 1* above); *During* started with the target position change and ended 50 ms after the completion of the saccade (we basically combined *epochs 2–4* as "saccade associated" to increase the number of cycles of the stimulus sampled); and *After* was the next 250 ms (equivalent to *epoch 5* above). The *During* time effectively contains all of the saccade-related periods. To perform a population analysis, we normalized bursting sepa-

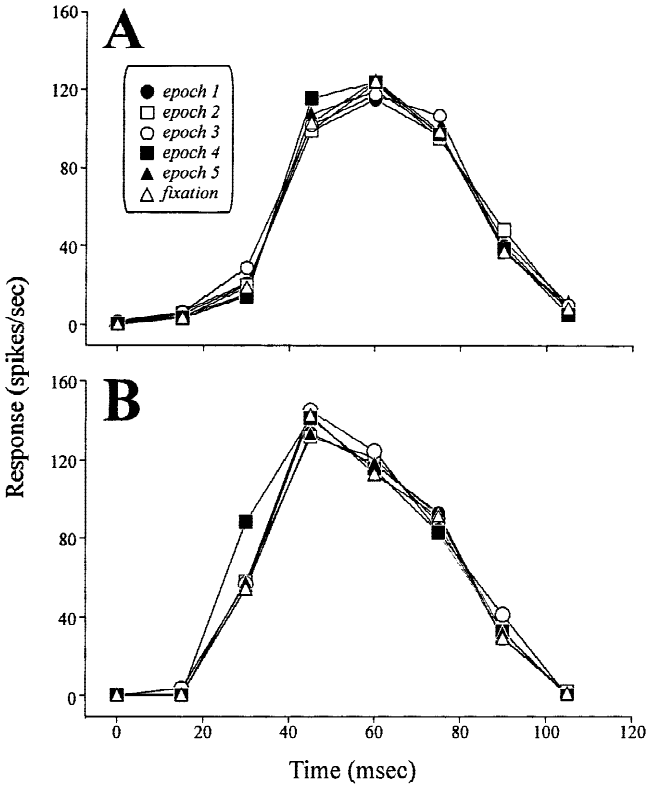

Fig. 3. The stimulus evoked responses of two parvocellular neurons (A and B) as in Figs. 1B and 1C.

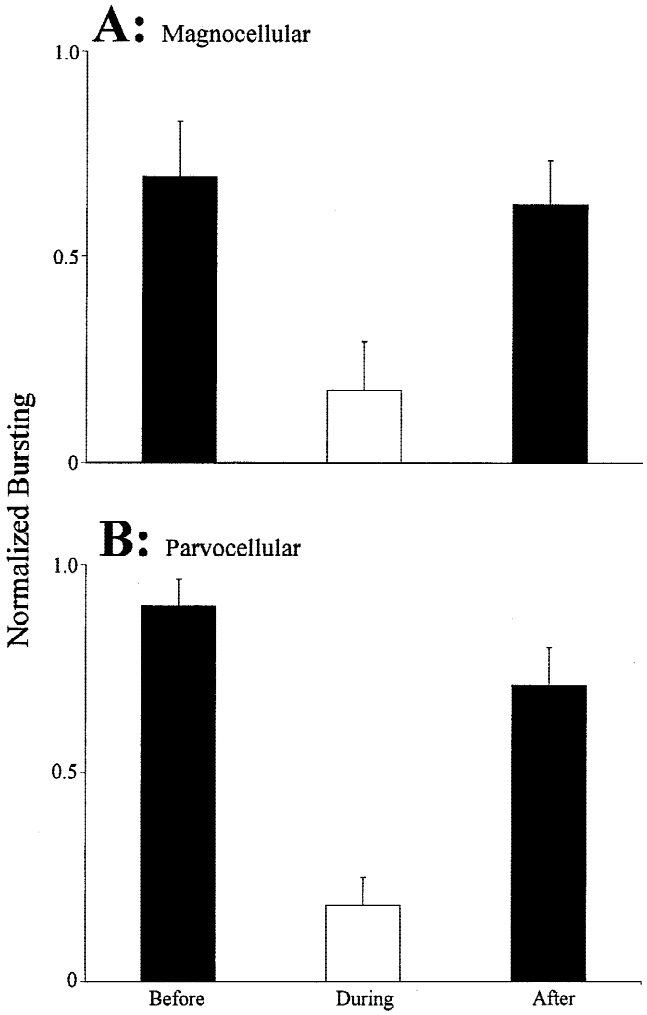

Fig. 4. Burst mode activity evoked by an 8-Hz full-field flashing stimulus for magnocellular (A; $n = 10$) cells and parvocellular (B; $n = 11$) cells. The relative amount of bursting has been normalized for comparison (see text for details). *Before* is equivalent to *epoch 1*; *During* is equivalent to *epochs 2–4*; and *After* is equivalent to *epoch 5*.

rately for M and P cells by determining the largest fraction of stimulus cycles evoking a burst in each cell during any of the three periods defined above and setting this to 1. Fig. 4A shows that bursting in magnocellular neurons was significantly reduced during the saccade period compared to the fixations before or after the saccade ($P < 0.01$). Likewise, Fig. 4B shows that bursting in parvocellular cells was equally inhibited during the saccadic/perisaccadic period compared to the fixations before or after the eye movement ($P < 0.01$).

Discussion

We have found that saccades do affect visual responsiveness of geniculate relay cells in the monkey in two ways. First, many M cells show an increased responsiveness during saccades, whereas responsiveness of P cells is unaffected by our measures. Second, the prevalence of burst mode responses is reduced in both M and P cells during saccades.

Relationship to previous studies of responses during saccades

Earlier studies have reported a variety of different responses of geniculate cells to saccades, and these reports are often difficult to reconcile with one another. For example, saccades were found to have little effect on the activity of either magnocellular or parvocellular neurons in the monkey LGN (Büttner & Fuchs, 1973). In another study, transmission through the primate geniculate was reported to be significantly reduced after saccades, an effect that was consistently greater in magnocellular than parvocellular cells (Bartlett et al., 1976). In contrast, our results suggest mild facilitation during and after saccades but no suppression. In cat, geniculate neurons were found in one study to display postsaccadic suppression when a patterned background was moved at saccadic velocity across a stationary eye (Noda, 1975). In another study, all Y cells and two-thirds of the X cells were found to respond with one or two activity peaks during and after saccades (Fischer et al., 1996). The excitation seen in Y cells may perhaps be comparable to the excitation we have seen in magnocellular cells, but we did not observe any effects on parvocellular cells (X cells in cats). Significant postsaccadic facilitation was reportedly stronger for X cells rather than Y cells (Lee & Malpelli, 1998). Furthermore, pretectal GABAergic cells, projecting to LGN interneurons, which could be antidromically activated by LGN stimulation, showed increased activity during saccades, suggesting a disinhibition of relay neurons during the eye movements (Schmidt, 1998; Fischer et al., 1998). It is difficult in this review of the literature to

determine any consensus for the effects of saccades on responses of geniculate neurons.

Neuronal basis of saccade-related effects on responsiveness

The effect of saccades on M cells, an increased visual responsiveness and reduction in burst mode responses, can be explained by a simple depolarization of these cells. That is, such a depolarization would both make the cells more responsive to visual stimuli and tend to inactivate the T channels underlying the Ca^{2+} conductance responsible for burst firing. This latter result would reduce bursting during saccades. Depolarization of M cells could come about by an increase in excitatory postsynaptic potentials (EPSPs) as well as a reduction of inhibitory postsynaptic potentials (IPSPs).

The most likely route of effect of saccades on geniculate relay cells would be brain-stem afferents, and in the monkey, the vast majority of these are cholinergic from the parabrachial region (Bickford et al., 2000). While the physiology of the brain-stem afferents has not been determined yet in the monkey, in the cat, these both directly excite relay cells and disinhibit them by inhibiting local GABAergic inputs from interneurons and the thalamic reticular nucleus (reviewed in Sherman & Guillery, 1996). Thus, a simple increase in baseline firing of these cholinergic brain-stem inputs during saccades could account for the effects we have documented for M cells.

However, this explanation does not so neatly explain the results for P cells. On the one hand, P cells also show a reduction of bursting during saccades, which suggests that these cells are somewhat depolarized. Yet there is no enhanced responsiveness to visual stimuli for these cells as would be expected if they were depolarized. Of course, there are many possible explanations for such an apparently nonlinear effect of presumed depolarization on visual responsiveness for P cells, but for the present we feel it best to limit our comments to highlighting this unusual response of P cells to saccades.

Relationship to saccadic suppression

Recent psychophysical data have suggested to the authors of those studies that the neural basis for saccadic suppression is likely to be at the level of the lateral geniculate nucleus and involve the M pathway relatively selectively (Burr et al., 1994). However, our results do not suggest any simple explanation at the level of the lateral geniculate nucleus for the phenomenon of saccadic suppression. Not only do we not see suppression of visual responses of geniculate cells during saccades, M cells actually show a moderate elevation of responsiveness, and this is hard to reconcile with response suppression expected for the M pathway. We do note that Campbell and Wurtz (1978) claim that the majority of the reduced visual responsiveness during saccades comes not from intrasaccadic suppression, but from backwards visual masking by a stable, clear image at the end of the saccade. It is interesting to note that the increased responsiveness of M cells roughly corresponds to the saccade end point. However, the neural mechanisms of visual masking are unknown, so it is at present unclear if or how these altered responses relate to such masking.

There is, however, one possible correlation with the effects we have observed and saccadic suppression. Both M and P cells show less bursting during saccades. It has been shown elsewhere that both burst and tonic response modes effectively relay retinal input to cortex (Guido et al., 1992, 1995; Mukherjee & Kaplan, 1995; Reinagel et al., 1999). A recent hypothesis offered about these relay modes is that tonic mode offers a more accurate linear relay, whereas burst mode offers a relay with better signal detectability (Sherman, 1996). This hypothesis, then, would predict that any significant reduction in burst firing could result in poorer stimulus detectability, and this is broadly consistent with saccadic suppression. If true, however, we see no evidence that M cells are more affected in terms of reduced burstiness during saccades than are P cells.

Acknowledgments

This work was supported by the National Eye Institute (Grant EY11409).

References

Bartlett, J.R, Doty, R.W., Lee, B.B. & Sakakura, H. (1976). Influence of saccadic eye movements on geniculostriate excitability in normal monkeys. *Experimental Brain Research* **25**, 487–509.

Bickford, M.E., Ramcharan, E., Godwin, D.W., Erisir, A., Gnadt, J. & Sherman, S.M. (2000). Neurotransmitters contained in the subcortical extraretinal inputs to the monkey lateral geniculate nucleus. *Journal of Comparative Neurology* **424**, 701–717.

Burr, D.C., Morrone, M.C. & Ross, J. (1994). Selective suppression of the magnocellular visual pathway during saccadic eye movement. *Nature* **371**, 511–513.

Büttner, U. & Fuchs, A.F. (1973). Influence of saccadic eye movements on unit activity in simian lateral geniculate and pregeniculate nuclei. *Journal of Neurophysiology* **36**, 127–141.

Campbell, F.W. & Wurtz, R.H. (1978). Saccadic omissions: Why we do not see a grey out during a saccadic eye movement. *Vision Research* **18**, 1297–1303.

Diamond, M.R., Ross, J. & Morrone, M.C. (2000). Extraretinal control of saccadic suppression. *Journal of Neuroscience* **20**, 3449–3455.

Fischer, W.H., Schmidt, M., Stuphorn, V. & Hoffman, K.P. (1996). Response properties of relay cells in the A-laminae of the cat's dorsal lateral geniculate nucleus after saccades. *Experimental Brain Research* **110**, 435–445.

Fischer, W.H., Schmidt, M. & Hoffman, K.P. (1998). Saccade-induced activity of dorsal lateral geniculate nucleus X- and Y-cells during pharmacological inactivation of the cat pretectum. *Visual Neuroscience* **15**, 197–210.

Guido, W. & Weyand, T. (1995). Burst responses in thalamic relay cells of the awake behaving cat. *Journal of Neurophysiology* **74**, 1782–1786.

Guido, W., Lu, S.-M. & Sherman, S.M. (1992). Relative contributions of burst and tonic responses to the receptive field properties of lateral geniculate neurons in the cat. *Journal of Neurophysiology* **68**, 2199–2211.

Guido, W., Lu, S.-M., Vaughan, J.W., Godwin, D.W. & Sherman, S.M. (1995). Receiver operating characteristics (ROC) analysis of neurons in the cat's lateral geniculate nucleus during tonic and burst response modes. *Visual Neuroscience* **12**, 723–741.

Holt, E.B. (1903). Eye movement and central anaesthesia. 1. The problem of anaesthesia during eye movement. *Psychological Monogram* **4**, 3–46.

Lee, D. & Malpelli, J.G. (1998). Effects of saccades on the activity of neurons in the cat lateral geniculate nucleus. *Journal of Neurophysiology* **79**, 922–936.

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

MacKay, D.M. (1970). Elevation of visual threshold by displacement of retinal image. *Nature* **225**, 90–92.

McCarley, R.W, Benoit, O. & Barrionuevo, G. (1983). Lateral geniculate nucleus unitary discharge in sleep and waking: State- and rate-specific aspects. *Journal of Neurophysiology* **50**, 798–818.

Mukherjee, P. & Kaplan, E. (1995). Dynamics of neurons in the cat lateral geniculate nucleus: *In vivo* electrophysiology and computational modeling. *Journal of Neurophysiology* **74**, 1222–1243.

Noda, H. (1975). Depression in the excitability of relay cells of lateral geniculate nucleus following saccadic eye movements in the cat. *Journal of Physiology* **249**, 87–102.

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

Ramcharan, E.J., Cox, C.L., Zhan, X.J., Sherman, S.M. & Gnadt, J.W. (2000*b*). Cellular mechanisms underlying activity patterns in the monkey thalamus during visual behavior. *Journal of Neurophysiology* **84**, 1982–1987.

Reinagel, P., Godwin, D., Sherman, S.M. & Koch, C. (1999). Encoding of visual information by LGN bursts. *Journal of Neurophysiology* **81**, 2558–2569.

Reppas, J.B., Usrey, W.M. & Reid, R.C. (1999). Saccadic modulation of visual responses in the lateral geniculate nucleus. *Society for Neuroscience Abstracts* **25**, 1427.

Robinson, D.A. (1964). The mechanics of human saccadic eye movement. *Journal of Physiology* **174**, 245–264.

Schmidt, M. (1998). Neurons in the cat pretectum that project to the dorsal lateral geniculate nucleus are activated during saccades. *Journal of Neurophysiology* **76**, 2907–2918.

Sherman, S.M. (1996). Dual response modes in lateral geniculate neurons: Mechanisms and functions. *Visual Neuroscience* **13**, 205–213.

Sherman, S.M. & Guillery, R.W. (1996). Functional organization of thalamocortical relays. *Journal of Neurophysiology* **76**, 1367–1395.

Steriade, M., McCormick, D.A. & Sejnowski, T.A. (1993). Thalamocortical oscillations in the sleeping and aroused brain. *Science* **622**, 679.

Wilson, J.R. & Noyd, W.W. (1998). Influence of saccades on the activities of P and M cells in the monkeys's lateral geniculate nucleus. *Society for Neuroscience Abstracts* **24**, 138.

Zhu, J.J. & Lo, F.S. (1996). Time course of inhibition induced by a putative saccadic suppression circuit in the dorsal lateral geniculate nucleus of the rabbit. *Brain Research Bulletin* **41**, 281–191.