Macaque vision after magnocellular lateral geniculate lesions

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Abstract
Ibotenic-acid lesions of the magnocellular portion of the macaque lateral geniculate nucleus were used to examine the role of the M-cell pathway in spatio-temporal contrast sensitivity. A lesion was placed in layer 1 of the lateral geniculate of each of two monkeys. Physiological mapping in one animal demonstrated that the visual-field locus of the lesion was on the horizontal meridian, approximately 6 deg in the temporal field. Visual thresholds were tested monocularly in the contralateral eye, and fixation locus was monitored with a scleral search coil to control the retinal location of the test target.

Three threshold measures were clearly disrupted by the magnocellular lesions. Contrast sensitivity for a 1 cycle/deg grating that drifted at 10 Hz was reduced from about twofold greater than, to about the same as, that for 10-Hz counterphase modulated gratings. Sensitivity for a very low spatial frequency (Gaussian blob), 10-Hz flickering stimulus was reduced so severely that no threshold could be measured. In addition, flicker resolution was greatly reduced at lower modulation depths (0.22), but not at higher depths (1.0). Two of the measured thresholds were unaffected by the lesions. Contrast sensitivity for 2 cycle/deg stationary gratings remained intact, and little or no effect on sensitivity was found for 1 cycle/deg, 10-Hz counterphase modulated gratings.

Together, these results suggest that the magnocellular pathway makes little contribution to visual sensitivity at low to moderate temporal frequencies. On the other hand, some contribution to detection sensitivity is evident at lower spatial and high temporal frequencies, especially for drifting stimuli. It appears that a major role of the magnocellular pathway may be to provide input to cortical mechanisms sensitive to rapid visual motion.

Keywords: Parallel pathways, Lateral geniculate, Magnocellular, Contrast sensitivity, Flicker, Macaque monkey

Introduction
The major retinocortical pathways in the macaque are those from the color-opponent retinal ganglion cells through the parvocellular layers of the geniculate (P pathway), and from the broadband retinal ganglion cells through magnocellular layers of the geniculate (M pathway) (Shapley & Perry, 1986). The anatomical and physiological properties of cells in these pathways have been studied in detail, and they are sufficiently different that they are likely to subserve different roles in visual processing (Merigan et al., 1989). The most striking difference is the vastly greater number of retinal ganglion cells in the P pathway, approximately eightfold more than in the M pathway (Perry et al., 1984). Neurons in the P pathway also show color-opponent physiological responses, and they are likely to provide the major input to the cortical “form and color” pathway (Maunsell & Newsome, 1987). These properties accord with behavioral studies that suggest that the P pathway is indeed important to the spatial resolution and chromatic sensitivity of the macaque (Merigan, 1989; Merigan et al., 1989; Schiller et al., 1990).

The magnocellular pathway is quite different. Neurons in this pathway have high contrast sensitivity and greater temporal resolution than neurons of the P pathway, and they provide the major input to the cortical “motion” pathway (Maunsell & Newsome, 1987). These properties provide some clues to the role of this pathway in vision, but except for a few reports (Merigan & Eskin, 1986; Schiller et al., 1990) there has been little direct assessment of its behavioral contribution. The present study examined the vision of macaques after lesions that were confined to a small portion of the visual-field representation of the magnocellular pathway. Parallel studies to examine the perceptual role of the P pathway are underway (Merigan et al., 1989).

Methods

Subjects
The subjects were two adult, female macaque monkeys (Macaca nemestrina) of approximately 5-kg body weight. They

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had free access to monkey chow, supplemented regularly with fresh fruit, and their water was withheld for approximately 20 h before threshold testing 5 days each week. All thresholds were measured monocularly during controlled fixation, and neither monkey had more than 0.5D of refractive error in either eye.

**Placement of lesions**

The monkeys were initially trained on the temporal resolution task described below, and then small ibotenic-acid lesions were placed in magnocellular layer 1 of the lateral geniculate nucleus, which relays signals only from the contralateral eye. For placement of the lesions, each monkey was anesthetized with Sufenta (sufentanil citrate 2 µg/kg/h) and paralyzed with Rocuron (vecuronium bromide 100 µg/kg/h). Recordings with platinum/iridium microelectrodes were used to locate the target visual-field representation in layer 1 of one lateral geniculate nucleus (left geniculate in monkey 311 and right geniculate in monkey 602). The electrode was then withdrawn and replaced by a glass probe that could be used for both recording and injection. Physiological recording was again used to place the tip of the pipette in the center of layer 1 of the geniculate at a visual-field representation approximately 6 deg temporal of the fovea on the horizontal meridian. Two microliters of ibotenic acid (5 µg/µl) was then injected by slow pressure injection.

At least 10 days later, under isoflurane anesthesia, a scleral search coil was implanted so that eye position could be monitored, and a stainless steel sleeve attached to the skull so that the monkey's head could be immobilized (Judge et al., 1980). The search coil was placed in the eye contralateral to the lesion. The monkeys were initially trained to perform the temporal resolution task with foveal fixation of the stimulus, and then, over several sessions, the fixation target was moved away from the test stimulus.

**Reconstruction of lesions**

At the conclusion of behavioral testing, the lesion placed in monkey 311 was reconstructed with anatomical and physiological techniques. Immediately prior to sacrifice, a detailed physiological map was made of layer 1, the magnocellular layer, and layers 4 and 6, the parvocellular layers that receive input from the tested eye. At the conclusion of physiological recording, the monkey was euthanized and perfused with a saline rinse followed by 4% paraformaldehyde in phosphate-buffered saline. The brain was removed, blocked, and 40-µm sections were cut on a freezing microtome. One section in four was reacted for cytochrome-oxidase activity (Wong–Riley, 1979), and another stained with cresyl violet. The lesion was then reconstructed from these anatomical sections using the location of electrode penetrations to precisely map it onto the visual field. The second animal is still being tested, and the lesion in this monkey will be reconstructed after the completion of testing.

**Apparatus and procedure**

**Temporal resolution**

The monkeys were seated in an acrylic chair at a distance of 35 cm from a green gallium phosphide light emitting diode (LED) (Hewlett Packard HLMP 3950), made spatially uniform with a diffuser. The stimulus (Fig. 1) subtended 0.65 deg of visual angle and was set in a white surround matched in luminance (480 cd/m²). This flicker stimulus differed from the counterphase Gaussian stimulus used subsequently (Figs. 1 and 7) in that it was smaller and had a very sharp border with the surround. Thus, the spatial composition of this stimulus is broadband, whereas that shown in Fig. 7 is dominated by low spatial frequencies. Monocular thresholds were measured with a temporal forced-choice procedure. Each trial began with the presentation of the small red fixation spot, which was positioned so that the LED test stimulus fell on the desired retinal locus. Control observations described in the discussion indicated that flicker could not be seen by portions of the retina away from the test site. While the monkey maintained fixation within ±0.3 deg of the fixation spot, two tones, each 800 ms in duration, were presented successively to mark the two intervals of the temporal forced-choice. The test stimulus was flickered during one of the intervals, and after the second tone the monkey was required to indicate which interval contained the stimulus, pressing one button for the first interval and another for the second interval. If the monkey's fixation moved outside of the ±0.3 deg window, or if it made a premature button press, the trial was aborted and a 3-s beeping tone was presented before the start of the next intertrial interval. Each intertrial interval was 4 s in length.

The test stimulus flickered continuously above the monkey's resolution limit (at 160 Hz), and for stimulus presentation the frequency was dropped briefly to the test frequency. The decrease in frequency followed a Gaussian waveform with s = 0.3 s, that was centered on one of the two intervals. The

![Fig. 1. Spatial-luminance profile of the stimuli used in this study. The flicker stimulus was a high intensity LED surrounded by a white background. The other stimuli were generated on the Conrac monitor. For the stationary grating, the solid line shows the luminance profile horizontally across the center of the stimulus. The other three stimuli were modulated sinusoidally in time and the solid line shows one extreme of the modulation, and the dashed line the other, while the arrows show the direction of luminance modulation. In one condition, the third stimulus from the top was drifted to the right rather than counterphase modulated. The grating moved laterally from the position represented by the solid curve past that shown by the dashed curve, while the aperture remained fixed.](image_url)
frequency tested varied from trial to trial following a staircase, decreasing one step (0.3 octave) after each error, and increasing, with probability 0.33 after each correct response. Flicker thresholds were measured at three levels of modulation depth: 1.0, 0.44, and 0.22, with modulation depth equal to \( \frac{L_{\text{max}} - L_{\text{min}}}{L_{\text{max}} + L_{\text{min}}} \) where \( L \) is the luminance. Daily sessions consisted of 200 trials, and thresholds were taken at 75% correct responding either by linear interpolation or by probit fits to the daily psychometric functions.

**Contrast sensitivity**

The seated monkey faced a 19-inch color monitor (Conrac 7211) at a distance of 211 cm. A fixation spot was projected onto the face of the monitor, and contrast thresholds were measured monocularly with small patches of horizontal grating displayed on the monitor. The grating targets were symmetric Gabor functions (cosinusoidal gratings multiplied by horizontal and vertical Gaussian weighting functions) generated on an Adage 3006 raster display unit and presented at a frame rate of 60 Hz (Fig. 1). The horizontal and vertical Gaussian weighting functions had equal space constants \( (s = 1.04 \text{ deg}) \). Thus, the grating was above 37% of peak contrast over a region extending 2.08 deg vertically and horizontally.

Four measures of contrast sensitivity were obtained for each monkey at two locations: 6 deg nasal and 6 deg temporal of the fovea along the horizontal meridian. Sensitivity was measured with (1) an unpatterned stimulus (Gaussian blob) of the same dimensions as the Gaussian weighting functions of the other stimuli, modulated sinusoidally at 10 Hz; (2) a 1-cycle/deg Gabor function, sinusoidally counterphase modulated at 10 Hz; (3) a 1-cycle/deg Gabor function with stationary envelope and a sinusoidal component that drifted to the right at 10 Hz (velocity = 10 deg/s); and (4) a 2-cycle/deg Gabor function that was unmodulated (stationary). The temporal waveform of each stimulus and the duration of the temporal forced-choice intervals were the same as described above.

**Results**

The extent of the geniculate lesion in animal 311 is illustrated in Fig. 2. Each panel shows the central portion of the temporal visual-field representation in a different geniculate layer. Small dots represent receptive-field centers that were mapped in each layer. A total of 31 receptive fields were plotted for layer 6, 19 for layer 4, and 5 for layer 1. The borders of the lesion in histological section were very sharply defined, as is characteristic of ibotenic-acid lesions (Newsome et al., 1985; Schwarzs et al., 1979). The borders were assigned to visual-field locations by interpolating between nearby recording sites, and the hatched regions in Fig. 2 mark the geniculate representations destroyed by the lesions. The circle represents the locus of the test stimulus during behavioral testing.

The lesion spread dorsally more than expected, and affected all layers to some degree. However, the extent and location of the affected representation differed from layer to layer. Importantly, in the region where the test stimuli were presented, layer 1 was completely lesioned and parvocellular layers 4 and 6 were entirely intact.

Figure 3 illustrates flicker resolution at five locations along the horizontal meridian of the visual field of the right eye for monkey 311 and the left eye for monkey 602. Arrows mark the eccentricity of the ibotenic-acid injection. The three curves represent different modulation depths ranging from 1.00-0.22. Flicker resolution was highest at the highest modulation depth, and declined about 15-30% at the lower modulation depths.

**Fig. 2.** Visual-field maps showing the portion of the visual-field representation lesioned in different geniculate layers in monkey 311. The horizontal and vertical lines represent the horizontal and vertical meridia of the visual field and the fixation point is at their intersection. A circle on each plot shows the limits of the visual test stimuli, squares show physiological recording sites where normal activity was found, and the hatched area shows a reconstruction of the lesion from anatomical sections and physiological mapping.

**Fig. 3.** Flicker resolution of two monkeys as a function of eccentricity along the horizontal meridian of the visual field. Thresholds were measured for the right eye of monkey 311 and the left eye of monkey 602. The location of the M pathway lesion at 6 deg in the temporal field is marked by an arrow. Data in the upper curve (circles) were obtained with sinusoidal flicker modulation of 1.00, the second curve (squares) at 0.44 modulation, and the third curve (triangles) at 0.22 modulation. Each point represents the mean ± s.d.
There was no effect of the M pathway lesion on flicker resolution at the highest modulation depth. However, at the lower modulation depths, a profound decrease was seen, which approached 50% at 22% modulation. These thresholds, and those described below, were measured from 2 weeks to about 12 months after the placement of the lesions and no evidence of recovery was seen during this time.

The flicker resolution results for 6-deg eccentricity on the lesion and control sides are replotted in Fig. 4 to illustrate modulation sensitivity as a function of temporal frequency (Lange, 1958). It can be seen in this figure that the losses in Fig. 3 may be better expressed as a decrease in modulation sensitivity after a lesion of the M pathway, rather than a reduction of temporal resolution per se.

Figure 5 shows that contrast sensitivity for a midspatial frequency (2 cycle/deg), unmodulated stimulus was not affected by a lesion of the M pathway for either of the two monkeys.

Measurements with 10-Hz modulated gratings are presented in Fig. 6. The first effect that can be seen in this figure is that contrast sensitivity for a 10-Hz counterphase modulated stimulus (filled symbols) was little affected by the M pathway lesion. Results for the drifting 10-Hz stimulus (open symbols) were more complicated. On the non-lesion (nasal field) side, sensitivity was markedly higher (almost twofold) for the drifting than the counterphase modulated stimulus. This result is consistent with previous reports of human sensitivity for these stimuli, e.g. Watson et al., 1980. On the lesion side, however, sensitivity for the drifting stimulus was reduced almost to the level seen for the counterphase modulated stimulus. Thus, the M lesion had a greater effect on sensitivity to the drifting stimulus, which was reduced to about the same level as that of the counterphase grating.

Contrast sensitivity for a low spatial (unpatterned), moderate temporal frequency (10 Hz) is shown in Fig. 7. Unlike the other stimulus conditions shown above, lesions of the magnocellular pathway reduced sensitivity sufficiently that no thresholds could be measured. The highest contrast presented was 0.80; thus, we can conclude that contrast sensitivity following the lesion was below 1.2.

Discussion

This study has shown that contrast sensitivity at low spatial frequencies, and possibly at high temporal frequencies, depends on the integrity of the magnocellular pathway. Complete sparing of parvocellular layers 4 and 6 in the tested portion of the visual field of monkey 311 makes it clear that this loss was not due to inadvertent damage to the parvocellular pathway. Our results further show that neither high-contrast flicker resolution nor luminance contrast sensitivity at low temporal frequencies is dependent on the pathway through magnocellular geniculate. The borders of the layer 1 lesion in monkey 311 extended well beyond the edges of the test stimuli, and the lesion involved a virtually complete loss of cells throughout, making it quite cer-
tain that our failure to find an effect on these functions was not due to an incomplete lesion. Together, these results suggest that the visibility of high-velocity stimuli (low spatial and high temporal frequencies) may be mediated by the magnocellular pathway, whereas the detection of other stimuli are independent of this pathway. These residual capacities could reflect function of the parvocellular pathway or that of other non-retino-geniculate pathways (Miller, 1980). However, parallel studies of lesions of the parvocellular pathway (Merigan et al., 1989) suggest that the residual vision seen here largely reflects the function of the parvocellular pathway.

Flicker resolution

The results shown in Figs. 2 and 3 of this paper indicate no effect of a magnocellular lesion on the resolution of high contrast flicker. The most obvious concern with this type of measurement is that detection might depend on light scattered from the stimulus to unlesioned portions of the visual field. The intense equiluminant surround made it unlikely that scattered light could be used, and this was verified by measurements of the nasal edge of the blind spot in human subjects using this stimulus. Flicker resolution fell off very abruptly and steeply at the edge of the blind spot, indicating that detection by non-tested portions of the retina was not possible.

It has been pointed out recently (Mayer et al., 1990) that the type of loss shown in Fig. 4 (primarily at high temporal frequencies but sparing the very highest frequency) is consistent with the loss of the high-frequency mechanism identified in temporal-frequency discrimination experiments (Mandler & Makous, 1984). This correspondence suggests that the magnocellular pathway might be the substrate for this high-frequency mechanism.

Our results for flicker resolution conflict with a recent report by Schiller and co-workers (Schiller et al., 1990), who found severely impaired flicker detection after a lesion of the magnocellular pathway. Their measurement differed in several respects from those reported in this paper; testing was binocular, stimuli were an 8 × 8 array of LEDs, a forced-choice psycho-

Our failure to find a defect in high-contrast flicker resolution suggests that either the parvocellular or magnocellular pathway could mediate this response. This is supported by recordings in the macaque geniculate that show that the response of both magnocellular and parvocellular neurons reaches a peak about 10–20 Hz and extends to frequencies well beyond 40 Hz (Derrington et al., 1984; Lee et al., 1989; Purpura et al., 1990). Of course, temporal resolution varies with eccentricity, which makes it important to compare magnocellular and parvocellular cells at the same eccentricity. Measurements of the temporal resolution of both cell types were collected by Sherman et al. (1984), and kindly made available by J. A. Movshon. These data show that there is substantial overlap in the temporal resolution of cells in these two pathways at all tested eccentricities, with the temporal resolution of many cells of each class exceeding 40 Hz.

Spatio-temporal contrast sensitivity

The data in Fig. 4 indicate that contrast sensitivity at low temporal and moderate spatial frequency is not disrupted by inactivation of the magnocellular pathway. A similar result has been described recently (Schiller et al., 1990). Moreover, recent studies in our laboratory of the effects of lesions in parvocellular geniculate (Merigan et al., 1989) suggest that contrast sensitivity under these spatio-temporal conditions is mediated by the parvocellular pathway. This conclusion is also consistent with the results of an earlier study that examined the spatio-temporal vision of macaques after chloroform-induced loss of those retinal ganglion cells that project to parvocellular geniculate (Merigan & Eskin, 1986). Such monkeys showed a severe reduction of contrast sensitivity at low temporal frequencies over a broad range of spatial frequencies. Collectively, these results suggest that the magnocellular pathway, or its cortical targets, may have a poor response to stimulation at low temporal frequencies. Results consistent with this conclusion have been reported recently by Purpura et al. (1990) for P and M retinal ganglion cells of the macaque. A detailed quantitative analysis of the temporal response of a small number of cells indicated that M cells had a substantially more phasic response than P cells, and this index was closely related to the responsivity of cells at low temporal frequencies. Such a pattern has not been obvious in reports of the response of geniculate neurons. Derrington and Lennie (1984) found steep temporal-frequency falloff in the response of both parvocellular and magnocellular neurons. This could not be the basis of poor magnocellular sensitivity at low temporal frequencies, as both pathways retained substantial sensitivity at frequencies as low as 0.2–0.3 Hz. In a recent paper, Lee et al. (1989) reported pronounced low temporal-frequency falloff for both parvocellular and magnocellular neurons, but only examined frequencies above 1 Hz. Thus, it is not yet clear if the low sensitivity of the magnocellular pathway at low temporal frequencies reflects properties of retinal and geniculate P and M cells, or if it arises later in the visual system.

A second finding of the present study is that the magnocellular pathway seems particularly important for the detection of
low spatial-frequency stimuli, at least at higher temporal frequencies. This is shown most clearly in Fig. 7 for detection of a counterphase modulated Gaussian patch. This stimulus was used because it is localized in both space (to test within the lesion locus) and spatial frequency (its spatial-frequency composition follows a Gaussian distribution centered at a spatial frequency of 0). Sensitivity for this stimulus was much more affected than that for the flickering LED whose sharp edges give it a broader composition of spatial frequencies. The magnocellular lesion also appeared to have a greater effect on sensitivity to the flickering LED (Fig. 4) than on sensitivity to the 10-Hz modulated grating. This may reflect both the higher temporal and spatial frequencies in the LED stimulus than in the 1 cycle/deg counterphase grating. An important role for the magnocellular pathway at low spatial and high temporal frequencies was also suggested by the earlier study (Merigan & Eskin, 1986) of macaques with severe loss of the parvocellular visual pathway. These monkeys had preserved contrast sensitivity only at low spatial and higher temporal frequencies. Physiological correlates of these observations are difficult to determine, since detailed spatio-temporal profiles have been reported for very few geniculate neurons. However, it does appear in the data of Derrington and Lennie (1984) that the relative sensitivity of magnocellular to parvocellular neurons is greatest at higher temporal and lower spatial frequencies. Of course this would represent a higher relative sensitivity only if variability of neuronal response were comparable at different spatial and temporal frequencies.

Response to motion

The findings shown in Fig. 6 suggest that the magnocellular pathway might play an important role in the detection of visual motion. The greater contrast sensitivity for drifting than counterphase modulated gratings that is evident in the nasal field measures is often ascribed to detection by directional (i.e. motion responsive) mechanisms (Pasternak, 1986; Wilson, 1985). Thus, a greater effect of magnocellular lesions on sensitivity for drifting stimuli could be interpreted as damage to a pathway specialized for motion response. A related observation is the recent report by Schiller et al. (1990) that, after magnocellular lesions, macaques could not detect the motion of a small group of dots on a field of random dots. This was interpreted as a specific deficit in motion perception. We hesitate about this explanation, however, because preliminary studies in our laboratory have shown that despite a loss of sensitivity for detection of rapidly moving gratings, monkeys are still able to discriminate their direction of motion. Thus, the issue of a unique contribution of magnocellular neurons to motion perception remains to be resolved.

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