Two Different Types of Y Cells in the Cat Lateral Geniculate Nucleus

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Yeh, Chun-I, Carl R. Stoelzel, and Jose-Manuel Alonso. Two different types of Y cells in the cat lateral geniculate nucleus. J Neurophysiol 90: 1852–1864, 2003; 10.1152/jn.00417.2003. The Y pathway in the cat visual system is traditionally viewed as a single channel that originates in the retina. However, most Y cells from the contralateral retina diverge to innervate two different layers of the lateral geniculate nucleus, suggesting a possible channel split: \( Y_C \) (Y geniculate cell in layer C) and \( Y_A \) (Y geniculate cell in layer A). We tested the functional significance of this anatomical divergence by comparing the response properties of simultaneously recorded \( Y_C \) and \( Y_A \) geniculate cells with overlapping receptive fields. Our results demonstrate that \( Y_C \) and \( Y_A \) cells significantly differ in a large number of temporal and spatial parameters including response latency, response transiency, receptive-field size, and linearity of spatial summation. Furthermore, for some of these parameters, the differences between \( Y_C \) and \( Y_A \) cells are as pronounced as the differences between Y and X cells in layer A. These results along with results from previous studies strongly suggest that Y retinal afferents diverge into two separate channels at the level of the thalamus.

INTRODUCTION

The visual system is organized in parallel pathways of information processing. Each pathway originates in a different type of retinal ganglion cell and travels fairly well segregated through the lateral geniculate nucleus (LGN) to the visual cortex. In the cat there are two main types of retinal ganglion cells, X and Y, that differ not only in their morphologies and response properties but also in their projections into the LGN (see Lennie 1980; Sherman 1985; Stone 1979 for reviews). Within the contralateral eye, X retinal ganglion cells project mostly to layer A, whereas Y cells diverge to project to layers C and A, which are the two main layers receiving contralateral input in cat LGN (Bowling and Michael 1980, 1984; Sur et al. 1982b, 1987; Tamamaki et al. 1995).

The divergence of Y retinal afferents into layers C and A could be designed to generate two different types of Y receptive fields: \( Y_C \) (Y geniculate cell in layer C) and \( Y_A \) (Y geniculate cell in layer A). In support of this hypothesis, \( Y_C \) and \( Y_A \) cells have different contrast sensitivities, different linearity of spatial summation (Frascella and Lehmkuhle 1984; Lee et al. 1992), and are likely to target different cortical structures (Boyd et al. 1998; Garey and Powell 1967; Gilbert and Kelly 1975; Holländer and Vanegas 1977; Humphrey et al. 1985b; LeVay et al. 1976, 1977). Against this hypothesis, \( Y_C \) and \( Y_A \) cells have similar morphologies (Guillery class 1; Friedlander et al. 1981; Guillery 1966; but see Ferster and LeVay 1978) and are not known to differ significantly in receptive-field size and response timing. Therefore whether \( Y_C \) and \( Y_A \) cells are “different enough” to be considered as separate functional types remains an open question.

One drawback of previous physiological comparisons between \( Y_C \) and \( Y_A \) cells is that only one cell was recorded at a given time. Because cell response properties depend substantially on retinal eccentricity (Frishman et al. 1983; Hoffmann et al. 1972; Wilson and Sherman 1976) and the state of the animal (Würgötter et al. 1998), accurate comparisons can be better made by simultaneously recording from \( Y_C \) and \( Y_A \) cells with overlapping receptive fields. By using this technical approach, here we demonstrate that \( Y_C \) and \( Y_A \) cells differ in response time course (e.g., latency, transiency) and receptive-field size. In addition, we confirm that \( Y_C \) and \( Y_A \) cells differ in the linearity of spatial summation, as was previously shown by Frascella and Lehmkuhle (1984). Therefore our results along with results from previous studies (Boyd et al. 1998; Ferster 1990a,b; Frascella and Lehmkuhle 1984; Garey and Powell 1967; Gilbert and Kelly 1975; Holländer and Vanegas 1977; Humphrey et al. 1985b; Lee et al. 1992; LeVay et al. 1976, 1977; Mitzdorf and Singer 1978) strongly suggest that Y retinal affrents diverge into two separate channels at the level of the thalamus. Preliminary results have appeared in abstract form (Yeh et al. 2000, 2001).

METHODS

Surgery and preparation

Cats were initially anesthetized with ketamine [10 mg/kg, intramuscular (im)] and thiopental sodium [20 mg/kg, intravenous (iv) supplemented as needed]. Lidocaine was administered topically or injected subcutaneously at all possible sources of pain and pressure. The animal was intubated and placed in a stereotaxic apparatus. The anesthesia was maintained with a continuous infusion of thiopental sodium (2–6 mg·kg\(^{-1}\)·h\(^{-1}\) in 0.9% saline, iv during surgery; 1–2 mg·kg\(^{-1}\)·h\(^{-1}\) in 0.9% saline, iv during recordings; additional doses supplemented as needed). Electrocardiogram (EKG), electroencephalogram (EEG), oxygen \((O_2)\) in blood, expired carbon dioxide \((CO_2)\), rectal temperature, heart rate, and blood pressure were monitored continuously and maintained within normal physiological limits throughout the experiment. Body temperature was kept between 37 and 38°C by using a thermostatically controlled heating blanket. A craniotomy was made in the skull (anterior, 5.5; lateral, 10.5) and...
the dura mater removed to access the LGN. The animal was then paralyzed with a continuous infusion of narcuron (0.2 mg·kg⁻¹·h⁻¹, iv) to minimize eye movements and was artificially ventilated to keep the expired CO₂ between 27 and 33 mmHg. Neosynephrine (10%) and atropine sulfate (1%) were applied to both eyes to retract the nictitating membranes and dilate the pupils. The eyes were covered with contact lenses to protect the corneas and focus visual stimuli presented at 114 cm in front of the animal. The positions of the optic disk and the area centrals were plotted on the tangent screen by using a fiber-optic light source (Pettigrew et al. 1979). All surgical and experimental procedures followed the guidelines of the U.S. Department of Agriculture and were approved by the Institutional Animal Care and Use Committee at the University of Connecticut.

Electrophysiological recordings and data acquisition

A matrix of 7 independently movable electrodes arranged circularly was introduced into the LGN (Eckhorn and Thomas 1993). The electrodes were very thin (80 μm rod; 25 μm at the shaft) and had impedance values of 3–6 MΩ (Thomas Recording, Marburg, Germany). A glass guide tube with an ID about 300 μm was added to the shaft probe of the multielectrode to reduce the inter-electrode distances to approximately 80–300 μm. The matrix of electrodes was then lowered into the brain, leaving the tip of the guide tube approximately 3 mm above the LGN. Each electrode was moved independently within the LGN; some electrodes were positioned in layer C and others in layer A. The angle of the multielectrode was adjusted precisely for each experiment (25–30° anterior–posterior; 2–5° lateral–central) to simultaneously record from cells with spatially overlapping receptive fields in both layers A and C. Figure 1A shows the retinotopic map of cat LGN (left) and the alignment of the electrodes used to record from cells with overlapping receptive fields (right). Throughout the text, X cells are represented in blue, Y_A cells in orange, and Y_C cells in green. All cells were recorded within 5–10° of the area centrals. Recorded signals from all 7 electrodes were amplified, filtered, and collected by a computer running the Discovery software package (Datawave Systems, Longmont, CO). For each cell, spike waveforms were identified initially during the experiment and verified off-line carefully by using cluster analysis software. Visual stimuli were generated with an AT-vista graphics card (Truevision, Indianapolis, IN) and shown on a 20-in. monitor (Nokia 445Xpro, Salo, Finland; frame rate, 128 Hz).

Receptive-field mapping

Geniculate receptive fields were mapped with white-noise stimuli and calculated by reverse correlation (Alonso et al. 2001; Reid et al. 1995, 1997, 2002; Sutter 1987, 1992). The white-noise stimulus was derived from a binary m-sequence (Reid et al. 1997; Sutter 1987, 1992), and spatially consisted of a 16 × 16 grid of black or white squares (pixels). Each frame (a 16 × 16 grid) was presented for 15.5 ms and the entire white-noise sequence lasted about 510 s. Each pixel in the white-noise stimulus was 0.81 deg² in size (0.9 × 0.9°) to allow simultaneous mapping of multiple geniculate cells with both small and large receptive fields. With this stimulus size, most of our receptive-field centers (97%) had at least two pixels. The average spatial stimulus was calculated for each delay between stimulus onset and neural response, and then normalized in units of spikes/s. For a given pixel and delay, a value of +1 indicates that the instantaneous rate of the neuron increased on average 1.0 spike/s after a white pixel and a value of −1 indicates that the instantaneous rate of the neuron increased on average 1.0 spike/s after a black pixel. Throughout the study receptive-field centers are shown as contour plots smoothed with a cubic spline. Each contour line represents from center to periphery 100 to 20%, with respect to the maximum response (Matlab, MathWorks, Natick, MA). In the reverse correlation map, on-responses are usually followed by off-rebounds and off-responses are followed by on-rebounds (see following text under Time course of the visual response). The on-responses and rebounds are shown as continuous lines; off-responses and rebounds are shown as discontinuous lines (Fig. 1B, left).

Receptive-field size and overlap

Both receptive-field size and overlap were calculated from responses to white-noise stimuli. The 20% contour line was chosen to determine the position of the receptive-field center, the receptive-field size, and the overlap with other receptive-field centers consistent with previous studies (Alonso et al. 2001). The time frame with the highest average firing rate was used for all of the measurements. The receptive-field size was quantified as the number of contiguous pixels within the 20% contour line (Fig. 1C, left). The receptive-field overlap between two cells was quantified as the percentage of pixels from the cell with the smaller receptive field that were superimposed with pixels from the cell with the larger receptive field (within the 20% contour line). The 20% contour line was used because it defines quite precisely the size of the geniculate center (measurements below 20% would be less accurate because of the presence of surround responses and background noise). It should be emphasized that the receptive-field size and overlap in this study refer exclusively to the receptive-field center and not the surround.

Time course of the visual response

The time course of the visual response was also calculated from responses to white-noise stimuli by reverse correlation. The “impulse response” was defined as the time course of the response evoked by the most effective stimulus pixel within the receptive-field center (the pixel that generated the maximum response). Most impulse responses were biphasic. For example, the impulse response of an on-center geniculate cell had a positive first phase (on-response) followed by a negative second phase (off-rebound); the impulse response of an off-center geniculate cell had a negative first phase (off-response) followed by a positive phase (on-rebound). It is not totally clear what is the mechanism that generates off- and on-rebounds. DeAngelis et al. (1995) indicated that the biphasic nature of the impulse response was attributed to “intrinsic properties of geniculate neurons.” Biphasic impulse responses are also likely to reflect the fact that geniculate neurons respond to sequences of white-noise pixels. For example, an on-center geniculate cell responds to sequences of black pixels immediately followed by white pixels (black-to-white sequence). Therefore its response will be correlated with both white pixels (short delay, on-response) and the preceding black pixels (longer delay, off-rebound). Throughout this study, on-responses and on-rebounds are represented by positive values; off-responses and off-rebounds are represented by negative values.

Impulse responses were normalized and fitted with a cubic spline to compare timing differences between simultaneously recorded cells (Fig. 1B, right). Each impulse response was normalized by its peak amplitude. The peak was defined as the maximum absolute value at the first phase of the impulse response (positive for on-center cells, negative for off-center cells). Because of this normalization procedure, throughout the study the peak values of the impulse responses are either 1 (on-center) or −1 (off-center). The rebound was defined as the maximum absolute value at the second phase of the impulse response (negative for off-rebounds, positive for on-rebounds). The zero crossing was defined as the zero value between both phases.

Four different temporal parameters were compared: peak time, rebound time, zero crossing time, and half-duration (Fig. 1C, middle and right). The half-duration was defined as the difference between the rebound time and the peak time (we use the half-duration of the impulse response as an estimate of response transience). We also calculated a ratio between the amplitude of the first and the second phase of the impulse response either as a biphasic index (Cai et al.

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FIG. 1. Several geniculate cells with overlapping receptive fields were simultaneously recorded at different geniculate layers. A: left: retinotopic map on a parasagittal section through middle of LGN in cat (adapted from Sanderson 1971). Most cells were recorded within 5° of the horizontal meridian (shown as pink square) and 5–10° of the vertical meridian. Right: closer view of site where cells were recorded. A matrix of 7 independently movable electrodes arranged circularly was introduced into LGN. Angle of multielectrode was adjusted precisely (25–30° anterior–posterior; 2–5° lateral-central) to simultaneously record from cells with spatially overlapping receptive fields across different geniculate layers. Throughout this study Y_C (Y cell in layer C) is shown in green, Y_A (Y cell in layer A) in orange, and X_A (X cell in layer A) in blue. B: receptive fields and impulse responses from four different types of cells obtained in lucky quadruple simultaneous-recording across entire depth of LGN. Left: receptive fields of an X_A cell (blue), a Y_A cell (orange), a Y_C cell (green), and a W cell (red). All cells had ON-center receptive fields and were simultaneously mapped by reverse correlation with white-noise stimuli. Y_C cell had the largest receptive-field size and X_A cell, the smallest. Right: impulse responses of 4 cells obtained at the strongest pixel of the receptive fields. The Y_C cell had the fastest impulse response (peak time, rebound time, zero crossing, and half-duration), followed by the Y_A cell, the X_A cell, and the W cell from the C layers, respectively. C: left: receptive-field size was calculated as the region contained within the 20% contour line of the receptive-field center mapped by white noise. Middle and right: temporal parameters were derived from impulse responses: peak time (absolute maximum of first phase), rebound time (absolute maximum of second phase), zero crossing (zero value between phases), half-duration or transience (difference between rebound time and peak time), and biphasic index (−1(rebound amplitude)/ (peak amplitude)).
1997) or rebound index (Alonso et al. 2001; Ussrey et al. 2000). The biphasic index was defined as $-1/\langle$rebound amplitude$\rangle/\langle$peak amplitude$\rangle$. The rebound index was defined as $-1/\langle$rebound area$\rangle/\langle$peak area$\rangle$, where the peak area is the integral of the impulse response before the zero crossing and the rebound area the integral of the impulse response after the zero crossing. Differences in biphasic index were all nonsignificant with one exception: in $Y_A X_A$ cell pairs the biphasic index was smaller for the $X_A$ cell ($P < 0.01$, Wilcoxon test). Differences in rebound index were all nonsignificant with one exception: in $Y_A X_A$ cell pairs the rebound index was smaller for the $Y_C$ cell ($P < 0.01$, Wilcoxon test). Because differences in the biphasic index or the rebound index were relatively rare, for the sake of simplicity, these two parameters will not be mentioned in the rest of the text.

Classification of geniculate cells

Geniculate cells were classified as Y or X based on the linearity of spatial summation measured with contrast reversing sinusoidal gratings (Enroth-Cugell and Robson 1966; Hochstein and Shapley 1976; Shapley and Hochstein 1975; So and Shapley 1979). We used at least two different spatial frequencies that were higher than the optimal; usually 0.55 cycle/deg and 1.1 cycle/deg. Because some Y cells can generate linear responses when tested with very low spatial frequencies, high spatial frequencies were used to unambiguously classify groups of Y and X geniculate cells that were simultaneously recorded (Hochstein and Shapley 1976; So and Shapley 1979). Each spatial frequency was tested at 8 different phases. The gratings were presented at 0.4 Hz and repeated 20 times at each spatial phase. The Y/X identification was always made from the responses to the highest spatial frequency that generated a significant response ($\geq 5$ spikes/50-ms bin). Cells that responded poorly ($< 5$ spikes/50-ms bin) were labeled as unclassified. The linearity of spatial summation was quantified as the ratio between the first and second Fourier harmonics ($F_2/F_1$). If the $F_2/F_1$ ratio was higher than 1 in more than half of the different spatial phases tested, the cell was classified as Y; otherwise the cell was classified as X. We also used the mean ratio (from 8 different phases) to represent spatial linearity in several figures of this report.

Cells recorded deep in the C layers (more than 500 $\mu$m below the transition A1–C) were discarded as possible W cells (n = 10; Stanford et al. 1983; Sur and Sherman 1982a; Wilson et al. 1976c). All 10 discarded cells responded poorly to contrast reversals (grating; $n = 3$: linear; $n = 7$: nonlinear) and had very slow impulse responses (peak times slower than 36 ms and $\geq 4.5$ ms slower than the slowest layer A cell simultaneously recorded). It is highly unlikely that the 7 nonlinear slow cells were Y-lagged, given that Y-lagged cells are very rare and have never been found in the C layers (Humphrey and Murthy 1999; Mastronarde et al. 1991). Overall, we recorded from 88 layer C cells and 146 layer A cells. In layer C, 75% of the cells were classified as Y (n = 66), 5.7% as X (n = 5), and 19.3% were unclassified (n = 17). In layer A, 39.7% of the cells were classified as Y (n = 58), 50.7% as X (n = 74), and 9.6% were unclassified (n = 14). In this study, we focus on three possible cell types: Y cell in layer A (Y_A), X cell in layer A (X_A), and Y cell in layer C (Y_C). We also used the mean ratio (from 8 different phases) to represent spatial linearity in several figures of this report.

Cross-correlation analysis

Correlograms were calculated with a time window of 10 ms (bin width of 0.1 ms) to search for cell pairs that fired in precise $\pm 1$-ms synchrony. The correlograms were band-pass filtered between 75 and 700 Hz and a level of significance was set at a probability of 1.2%, assuming a normal distribution in the baseline amplitudes after filtering. Tight correlations that passed this level of significance were taken as an indication that a cell pair shared a common retinal input (Alonso et al. 1996; Ussrey et al. 1998). The correlation strength was calculated from the unfiltered correlograms (1 ms around maximum) after subtracting the baseline. The baseline was defined as the average value of the correlogram at both sides of the central peak (within 2–3 ms from zero).

RESULTS

Geniculate cells were simultaneously recorded from layers C and A of the cat LGN with a multielectrode matrix (Eckhorn and Thomas 1993). For each experiment, the angle of the multielectrode was adjusted precisely to match the retinotopic map of the LGN [Fig. 1A, left; adapted from Sanderson (1971)] and record from several cells with overlapping receptive fields (Fig. 1A, right). Throughout the entire study $Y_C$ cells are shown in green, $Y_A$ cells in orange, and $X_A$ cells in blue (Fig. 1A, right). Figure 1B shows the receptive-field centers and response time courses of 4 cells that were simultaneously recorded across the entire depth of the LGN in a quadruple recording. The receptive fields are shown as contour plots (Fig. 1B, left) and the response time courses as biphasic impulse responses. Because these 4 cells were all on-center, they all had positive first phases followed by negative phases (Fig. 1B, right; see METHODS for details). The 20% contour line was chosen to determine the position of the receptive-field centers, the receptive-field sizes, and receptive-field overlap (Fig. 1C, left; see METHODS). The response time course was measured by calculating several point values within the impulse response (Fig. 1C, middle and right).

Differences between $Y_C$ and $Y_A$ cells

Simultaneous recordings from $Y_C$ and $Y_A$ cells with overlapping receptive fields allowed us to precisely compare their response properties. Figure 2A shows a scatter plot of all $Y_C Y_A$ cell pairs represented as a function of the peak time of their impulse responses (each circle represents a $Y_C Y_A$ cell pair). Most circles are below the diagonal indicating that the $Y_C$ cells had faster peak times than the $Y_A$ cells. We calculated the magnitude of the peak–time difference by subtracting the $Y_A$ peak time from the $Y_C$ peak time for each cell pair and then averaging the results for all pairs. The peak–time difference was equal to $-2.53$ ms, indicating that the peak of the impulse response was on average $2.53$ ms faster for $Y_C$ than for $Y_A$ cells. This difference was highly significant ($P < 0.001$, Wilcoxon test). The right side of the Fig. 2A shows examples of cell pairs obtained from three different regions in the scatter plot. In most of the cell pairs (72%) the peak time of the impulse response was faster for the $Y_C$ cell than for the $Y_A$ cell. $Y_C$ and $Y_A$ cells also differed in their receptive-field sizes. In most cell pairs recorded, the receptive field was larger for the $Y_C$ cell than for the $Y_A$ cell, as shown in the scatter plot of Fig. 2B (percentages are shown on the right of the figure). We measured the magnitude of the difference in receptive-field size by calculating a ratio for each cell pair (receptive-field size of $Y_C$/receptive-field size of $Y_A$) and then averaging the results obtained for all pairs. The $Y_C/Y_A$ ratio was 1.84, indicating...
that the receptive-field size was almost twice as large for the $Y_C$ cell than for the $Y_A$ cell. Once more this difference was highly significant ($P < 0.001$, Wilcoxon test).

In addition to the peak time and receptive-field size, $Y_C$ and $Y_A$ cells significantly differed in three other additional temporal parameters: zero crossing (Fig. 3A), rebound time (Fig. 3B), and half-duration of the impulse response (Fig. 3C). We calculated the magnitude of these differences by using the same method described above for peak time. The average differences of $Y_C - Y_A$ were as follows: zero crossing $= -3.86$ ms,
rebound time = −4.48 ms, half-duration = −1.94 ms. We also compared the linearity of spatial summation by calculating the ratio \( F_2/F_1 \) of \( Y_C \) and \( Y_A \). This ratio was 3.9, indicating that \( F_2/F_1 \) was about 4 times higher for \( Y_C \) cells than for \( Y_A \) cells (Table 1).

**Differences between \( Y \) and \( X \) cells**

These results demonstrate that \( Y_C \) and \( Y_A \) cells significantly differ in several temporal and spatial response properties. How do these differences compare with the differences between \( Y_A \) and \( X_A \) cells? The answer to this question is important because \( Y \) and \( X \) cells are generally accepted as separate cell types (Boycott and Wässle 1974; Bullier and Norton 1979; Cleland et al. 1971; Enroth-Cugell and Robson 1966; Guillery 1966; Hoffmann et al. 1972; Levay and Ferster 1977; So and Shapley 1979). Similarly to \( Y_C Y_A \) cell pairs, \( Y_A \) and \( X_A \) cells differed in the peak time (\( Y_A - X_A = -3.90 \) ms, \( P < 0.001 \), Fig. 4A) and receptive-field size (\( Y_A/X_A = 1.62, P < 0.001 \), Fig. 4B). The percentage of \( Y_C \) cells with faster impulse responses than those of \( Y_A \) cells (72%) was similar to the percentage of \( Y_A \) cells with faster impulse responses than those of \( X_A \) cells (76%) and such similarity in percentages was also found for receptive-field size (62% of \( Y_C \) vs \( Y_A \) and 64% of \( Y_A \) vs \( X_A \)). In spite of this striking parallel in percentages, the magnitude of the differences in most of the parameters tested was larger between \( Y_A \) and \( X_A \) cells than between \( Y_C \) and \( Y_A \) cells. In fact, the largest differences were found in \( Y_C X_A \) cell pairs (\( Y_C - X_A \) in peak time = −5.26 ms, \( P < 0.001 \); \( Y_C/X_A \) in receptive-field size = 2.62, \( P < 0.001 \); Fig. 4, D and E). The impulse responses of \( Y \) and \( X \) cells differed not only in the peak time but also in zero crossing, rebound time, and half-duration. In addition \( X \) and \( Y \) cells are known to differ in their linearity of spatial summation and their morphology (see Len-

**TABLE 1. Temporal and spatial parameters that differentiate \( Y_C \), \( Y_A \), and \( X_A \) cells (measured in all cell pair combinations)**

<table>
<thead>
<tr>
<th></th>
<th>( Y_C Y_A )</th>
<th>( Y_A X_A )</th>
<th>( Y_C X_A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Time</td>
<td>−2.53***</td>
<td>−3.9***</td>
<td>−5.26***</td>
</tr>
<tr>
<td>Difference</td>
<td>−3.86***</td>
<td>−6.00***</td>
<td>−8.24***</td>
</tr>
<tr>
<td>Zero-Crossing</td>
<td>−4.48***</td>
<td>−9.03***</td>
<td>−13.27***</td>
</tr>
<tr>
<td>Difference</td>
<td>−1.94**</td>
<td>−5.13***</td>
<td>−7.91***</td>
</tr>
<tr>
<td>Rebound Time</td>
<td>1.84***</td>
<td>1.62***</td>
<td>2.62***</td>
</tr>
<tr>
<td>Difference</td>
<td>3.90*</td>
<td>16.27***</td>
<td>57.35***</td>
</tr>
<tr>
<td>Half-Duration</td>
<td>1.62***</td>
<td>16.27***</td>
<td>57.35***</td>
</tr>
<tr>
<td>Difference</td>
<td>3.90*</td>
<td>16.27***</td>
<td>57.35***</td>
</tr>
<tr>
<td>Receptive-Field</td>
<td>1.84***</td>
<td>16.27***</td>
<td>57.35***</td>
</tr>
<tr>
<td>Size Ratio</td>
<td>3.90*</td>
<td>16.27***</td>
<td>57.35***</td>
</tr>
</tbody>
</table>

The values for the 3 rows (\( Y_C Y_A \), \( Y_A X_A \), \( Y_C X_A \)) were obtained by the same method, which is explained for the first row (\( Y_C Y_A \)). Peak time: the \( Y_A \) peak time was subtracted from the \( Y_C \) peak time (i.e., \( Y_C - Y_A \)) for each cell pair and then the results were averaged. Zero-crossing, Rebound time, and Half-duration: same as for Peak time. Receptive-field size: we calculated a ratio (\( Y_A \) receptive-field size)/(\( Y_A \) receptive-field size) for each cell pair and then the results were averaged. Linearity ratio: we calculated a ratio (\( F_2/F_1 \) for \( Y_C \))/(\( F_2/F_1 \) for \( Y_A \)) for each cell pair and then averaged all pairs. * \( P < 0.05 \), ** \( P < 0.01 \), *** \( P < 0.001 \); Wilcoxon test.
Y<sub>A</sub> - X<sub>A</sub> comparison

A Peak Time

B Receptive-Field Size

C Spatial Linearity

Y<sub>C</sub> - X<sub>A</sub> comparison

D Peak Time

E Receptive-Field Size

F Spatial Linearity

FIG. 4. Y cells (Y<sub>A</sub> or Y<sub>C</sub>) have faster peak times and larger receptive-field sizes than X cells. A: Y<sub>C</sub>X<sub>A</sub> pairs plotted as function of peak time. In most cases (76%, n = 47), Y<sub>C</sub> cells had faster impulse responses than X<sub>A</sub> cells (Y<sub>C</sub> - X<sub>A</sub> = -3.90 ms, P < 0.001). B: Y<sub>C</sub>X<sub>A</sub> pairs plotted as function of receptive-field size. On average, Y<sub>C</sub> cells had receptive fields 1.62 times larger than X<sub>A</sub> cells (64%, n = 40, P < 0.001). C: Y<sub>C</sub>X<sub>A</sub> pairs plotted as function of spatial linearity calculated by averaging F<sub>2</sub>/F<sub>1</sub> ratio measured at 8 different spatial phases. A cell was classified as Y if it had an F<sub>2</sub>/F<sub>1</sub> ratio greater than 1 in more than half of spatial phases tested; otherwise it was classified as X (see METHODS for details). There are slight differences in classification depending on how F<sub>2</sub>/F<sub>1</sub> ratios are measured (e.g., F<sub>2</sub>/F<sub>1</sub> ratio for phase that generates strongest response, F<sub>2</sub>/F<sub>1</sub> averaged across spatial phases, etc.). In this graph, spatial linearity was measured as average across all 8 spatial phases tested (4 out of 62 cells classified as Y had average F<sub>2</sub>/F<sub>1</sub> slightly lower than those classified as X cells). D: Y<sub>C</sub>X<sub>A</sub> pairs plotted as function of peak time. Y<sub>C</sub> cells had faster peak time than X<sub>A</sub> cells (89%, n = 59). In very few cases the impulse response of X<sub>A</sub> cell was as fast as (9%, n = 6) or faster (2%, n = 1) than the impulse response of Y<sub>C</sub> cell. On average, peak time of Y<sub>C</sub> cells is 5.26 ms faster than X<sub>A</sub> cells (P < 0.001). E: Y<sub>C</sub>X<sub>A</sub> pairs plotted as function of receptive-field size. Receptive-field size of Y<sub>C</sub> cell was usually larger (83%, n = 55) than X<sub>A</sub> cell. Only rarely was receptive field of the Y<sub>C</sub> cell equal to (6%, n = 4) or smaller (11%, n = 7) than the receptive field of the X<sub>A</sub> cell. On average, receptive fields were 2.62 times larger in Y<sub>C</sub> cells than X<sub>A</sub> cells (P < 0.001). F: Y<sub>C</sub>X<sub>A</sub> pairs plotted as a function of the spatial linearity calculated by averaging the F<sub>2</sub>/F<sub>1</sub> ratio measured at 8 different spatial phases. In 2 out of 66 cases averaged F<sub>2</sub>/F<sub>1</sub> was larger for X<sub>A</sub> cell than for Y<sub>C</sub> cell (see METHODS for classification criteria and C above).

Differences between Y<sub>C</sub>, Y<sub>A</sub>, and X<sub>A</sub> cells measured in triple simultaneous recordings

Differences between Y<sub>C</sub>, Y<sub>A</sub>, and X<sub>A</sub> cells could be compared more precisely in simultaneous recordings from triplets of cells with overlapping receptive fields (n = 34). Figure 5 (top) shows the receptive-field centers and impulse responses of three simultaneously recorded Y<sub>C</sub>, Y<sub>A</sub>, and X<sub>A</sub> cells (cell triplet). In this example, the Y<sub>C</sub> cell had the largest receptive field and fastest impulse response and the X<sub>A</sub> cell the smallest receptive field and slowest impulse response. In the analysis of all the cell triplets, again we found that Y<sub>C</sub> cells had larger receptive fields, faster peak times, and stronger nonlinearities than those of Y<sub>A</sub> cells (receptive-field size: Y<sub>C</sub> > Y<sub>A</sub> in 85% of triplets, Y<sub>C</sub>/Y<sub>A</sub> = 1.81, P < 0.001; peak time: Y<sub>C</sub> < Y<sub>A</sub> in 82% of triplets, Y<sub>C</sub> - Y<sub>A</sub> = -3.46 ms, P < 0.001; F<sub>2</sub>/F<sub>1</sub>; Y<sub>C</sub> > Y<sub>A</sub> in 65% of the triplets, Y<sub>C</sub>/Y<sub>A</sub> = 4.3, P < 0.03). Interestingly, in the analysis of cell triplets, the differences in
peak time and receptive-field size between Y\(_C\) and Y\(_A\) cells were definitely not smaller than the differences between Y\(_A\) and X\(_A\) cells (receptive-field size: Y\(_C\)/X\(_A\) = 1.32, \(P < 0.05\); peak time: Y\(_A\) - X\(_A\) = -1.28 ms, \(P < 0.06\)). The histograms in Fig. 5 (bottom) illustrate these differences [the absolute value was chosen as the best representation of the magnitude differences; a nearly identical histogram was obtained by using (Y\(_C\) - Y\(_A\))/(Y\(_A\) - X\(_A\)).]

It is generally assumed that Y-receptive fields are 3 times larger than X-receptive fields both at the level of the retina and within the LGN (So and Shapley 1979; see also Shapley and Lennie 1985 for review). This notion derives from careful measurements of the spatial frequency tuning of X and Y cells recorded in layer A with a single electrode (So and Shapley 1979). As shown here, measurements of receptive-field size with white noise leads to a slightly different conclusion. Whereas the Y\(_C\)/X\(_A\) receptive-field ratio approaches 3:1, the Y\(_A\)/X\(_A\) ratio is smaller than 2:1. Similarly, the differences in response latency are larger between Y\(_C\) - X\(_A\) than between Y\(_A\) - X\(_A\). It seems as if Y\(_A\) cells had found a compromise between the high spatial resolution of the X\(_A\) pathway and the fast temporal resolution of the Y\(_C\) pathway. This “intermediate status” of Y\(_A\) cells is further supported by cluster analysis. Figure 6 shows multiple Y\(_C\), Y\(_A\), and X\(_A\) cells plotted in a 3D space determined by the receptive-field size, peak time, and half-duration of the impulse responses (Fig. 6A: all cells, Fig. 6B: Y\(_C\)-Y\(_A\)-X\(_A\) triplets obtained in simultaneous recordings). At the top of the 3D plot, a copy of the same data points is shown only for Y\(_C\) and X\(_A\) cells. The top plot illustrates the clean separation of Y\(_C\) and X\(_A\) cells. The bottom plot illustrates the “intermediate” status of the Y\(_A\) cells. As shown in this figure, Y\(_C\) and X\(_A\) cells can be reliably separated into two different clusters (K-means cluster analysis and chi-square test, \(P < 0.01\) for Y\(_C\), \(P < 0.001\) for X\(_A\)), whereas Y\(_A\) cells lie in between.

Overall, these results indicate that Y\(_C\), Y\(_A\), and X\(_A\) cells significantly differ in several temporal and spatial parameters. Y\(_C\) cells have the largest receptive fields and generate the fastest, most transient, and least linear responses to visual stimuli. X\(_A\) cells have the smallest receptive fields and generate the slowest, least transient, and most linear responses. The response properties of Y\(_A\) cells fall in between Y\(_C\) and X\(_A\) cells.

**Correlated firing between Y\(_C\) and Y\(_A\) cells**

The finding that Y\(_C\) and Y\(_A\) cells have different properties is puzzling because the anatomy indicates that almost every Y retinal afferent from the contralateral eye projects to both layers A and C (Bowling and Michael 1980, 1984; Sur et al. 1982b, 1987; Tamamaki et al. 1995). This puzzle can be addressed in part by measuring the correlated firing between Y\(_C\) and Y\(_A\) cells. It was previously shown that cells sharing a common retinal afferent within layer A fire in a tight 1-ms synchrony (Alonso et al. 1996; Usrey et al. 1998). If Y\(_C\) and Y\(_A\) cells share a retinal afferent they should also generate tight correlated firing. Figure 7A shows an example of a pair of Y\(_C\) and Y\(_A\) cells with overlapping receptive fields that were simultaneously recorded. The Y\(_C\) cell had a larger receptive field and faster impulse response than those of the Y\(_A\) cell. Importantly, the receptive fields were of the same sign (off-center) and the receptive-field overlap was almost total. The bottom of Fig. 7A shows a correlogram with a very narrow peak centered at zero, indicating that the two cells were likely to share a retinal afferent.

The great majority of Y\(_C\)/Y\(_A\) cell pairs (\(n = 9/11\)) with receptive fields overlapped more than 80%, and of the same sign, showed tight correlated firing. However, the average strength of the Y\(_C\)/Y\(_A\) tight correlations (7.5%) was almost half the value reported for tight correlations within layer A (13%; Alonso et al. 1996). This finding seems to indicate that most Y\(_C\)/Y\(_A\) cells with overlapping receptive fields of the same sign share common retinal afferents. However, the shared afferents are weaker across layers than within the same layer.

**Discussion**

Most books on neuroscience describe three different types of channels in the cat visual pathway—X, Y, and W—each including on-center and off-center cells (Leventhal 1991; Orban 1984; Payne and Peters 2002; Pettigrew et al. 1986; Rodieck 1973; Sherman and Guillery 2001; Steriade et al. 1990; Stone 1983). However, the total number of channels is likely to be much higher. Berson and his colleagues identified more than 12 morphologically different types of retinal ganglion cells (Berson et al. 1998, 1999; Isayama et al. 2000; O’Brien et al. 2002; see also Dacey et al. 2003 and Masland 2001), and Cleland et al. identified ≥8 different functional types (Cleland et al. 1971, 1974a,b). Moreover, each of the parallel pathways originating in the retina is likely to diverge into more specialized channels as the information progresses in the visual pathway.

The anatomy of the Y pathway in the cat is very suggestive of this channel divergence/specialization. Y retinal afferents...
from the contralateral eye diverge to innervate two different layers within the LGN (layers C and A) and, as suggested here, this anatomical divergence could translate into two different types of Y receptive fields.

Are Y_C and Y_A two different cell types?

Although the idea of two different Y channels has been in the literature since the 1970s, it has not been systematically tested. The closest attempt was done by Frascella and Lehmkuhle (1984) and Lee et al. (1992). However, both studies had a relatively small sample of cells (19 Y_C in Frascella and Lehmkuhle (1984); 9 Y_C in Lee et al. 1992) and precise comparisons were further complicated by the fact that the cells were not simultaneously recorded and were not precisely matched in retinotopy. In spite of these technical limitations, Frascella and Lehmkuhle (1984) recorded from 19 Y_C cells, all within 15° of the area centralis, and did a detailed quantification of contrast sensitivity (using different temporal and spatial frequencies) and linearity of spatial summation (using different contrasts). By doing so, these authors clearly demonstrated that Y_C cells have higher contrast sensitivity and stronger nonlinearities than those of Y_A cells. Our study confirms the result that Y_C cells have stronger nonlinearities than those of Y_A cells and, in addition, it reports the following new findings: 1) Y_C and Y_A cells significantly differ in their receptive-field sizes and the peak time, zero crossing, rebound time, and half-duration of their impulse responses. 2) The differences in receptive-field size between Y_C and Y_A cells are not smaller in magnitude than the differences between Y_A and X_A cells. 3) Cluster analysis based on receptive-field size and response timing can successfully separate X_A cells from Y_C cells, whereas Y_A cells lie in between the two clusters.

Are these findings enough to propose that Y_C and Y_A cells are two different “cell types”? Rodieck and Brening (1983) argued that a “natural cell type” should be defined by simultaneously considering a large number of parameters, both quantitative and qualitative (see also Rowe and Stone 1977). The greater the number of parameters, the sharper and more individualistic the definition of cell type is. Based on this definition, Y_C and Y_A cells could be considered as separate “natural cell types” because they differ in several parameters including receptive-field size, response latency, response transience, linearity of spatial summation, and contrast sensitivity. It is important to remember the words of Rodieck and Brening (1983): “The notion that a given cell type is indivisible retains the character of a hypothesis. The inclusion of an additional parameter always has the potential for further subdividing the clusters.” On the other hand, it is also important to emphasize that the differences between Y_C and Y_A cells are relatively modest compared to the differences between Y

FIG. 6. Y_C and X_A cells could be reliably separated into two different clusters in 3D space determined by receptive field size, peak time, and response half-duration (P < 0.01 for Y_C; P < 0.001 X_A; K-means cluster analysis and chi-square). Y_A cells were equally found in two clusters. A: 3D graph representing entire population of Y_C, Y_A, and X_A cells (n = 198, Y_C in green, Y_A in orange, X_A in blue). Ninety-three percent of these cells (n = 184) were segregated into two different clusters by K-means cluster analysis: Cluster 1 (C1) and Cluster 2 (C2). On average, cells in C1 had larger receptive-field sizes (C1/C2 = 6.1/4.9), faster peak times (C1/C2 = 27.8/36.2), and shorter half-durations (C1/C2 = 27.7/34.4) than cells in C2. Y_C cells were found more frequently in C1 (68%, P < 0.01), X_A cells were found predominantly in C2 (87%, P < 0.001), and Y_A cells were equally distributed in both clusters. To better illustrate two main clusters, same point values are shown at top of 3D graph only for Y_C and X_A cells. B: same for triplets of simultaneously recorded Y_C—Y_A—X_A cells. This graph also shows tendency for Y_C and X_A cells to form different clusters with Y_A cells lying in between.
and X cells (Table 1), particularly when considering the linearity of spatial summation and the morphology. Therefore Y_C and Y_A cells may not be different cell types but the extremes of a continuum.

How may the different response properties of Y_C and Y_A cells be generated?

Even if Y_C and Y_A cells are the extremes of a continuum, it is still somewhat surprising that they are so different. After all, almost every Y retinal afferent from the contralateral eye projects to both geniculate layers, layer A and layer C. An explanation to this puzzle could be advanced if we make the following assumptions.

1) Y_C and Y_A receptive fields are likely to be generated from common Y retinal afferents. This assumption is supported by two different findings. First, almost every Y retinal afferent from the contralateral eye projects to both layers A and C (Bowling and Michael 1980, 1984; Sur et al. 1982b, 1987; Tamamaki et al. 1995). Second, cross-correlation analysis indicates that Y_C and Y_A cells with overlapping receptive fields of the same sign share common retinal afferents (Yeh et al. 2000).

2) It is likely that more retinal afferents converge on Y_C cells than Y_A cells. A larger convergence, and consequently a faster synaptic integration, is consistent with the higher contrast sensitivity and faster impulse responses of Y_C cells. Moreover, the larger convergence could also explain the larger receptive-field sizes of Y_C cells.

3) Each retinal afferent probably makes a smaller number of contacts with a Y_C cell than with a Y_A cell. In support of this assumption, Y retinal afferents make less synapses in layer C than layer A (Sur et al. 1982b, 1987) and tight correlated firing is weaker between Y_C and Y_A cells than between layer A cells (Alonso et al. 1996).

These three assumptions are summarized in a cartoon represented in Fig. 7B. The square boxes represent three geniculate cells: two Y_A cells (in orange) and one Y_C cell (in green). A single retinal afferent makes a larger number of synapses with the Y_A cell than with the Y_C cell (the number of synapses are represented by the size of the black circle). Because the Y_C cell receives input from another retinal afferent, the Y_C cell receives more retinal synapses in total than does the Y_A cell. The correlated firing between the Y_A cell and the Y_C cell is relatively weak because there is only one shared retinal afferent that makes a relatively weak connection in layer C. This cartoon illustrates the simplest possible circuit. In a more complicated version, there could be more retinal afferents for each Y_A cell and even more for each Y_C cell.
Possible functional significance of two Y-channels

The differences between Y\textsubscript{C} and Y\textsubscript{A} cells would be irrelevant if their projections within the cortex were not segregated. Several previous studies have suggested that this is not the case. First, cells in layers C and A of LGN target different cortical areas—most layer C cells project to area 18, whereas most layer A cells project to area 17 (Boyd et al. 1998; Bullier et al. 1984; Garey and Powell 1967; Geisert 1980; Gilbert and Kelly 1975; Holländer and Vanegas 1977; Humphrey et al. 1985a,b; LeVay and Ferster 1977; Niimi and Sprague 1970). Second, the layer C cells that do project to area 17 are likely to target different cortical layers than the layer A cells (Boyd and Matsubara 1996; Bullier and Henry 1979; Ferster and LeVay 1978; Freund et al. 1985b; Gilbert and Kelly 1975; Humphrey et al. 1985a; LeVay and Gilbert 1976; Mullikin et al. 1984). Third, Y cells projecting to area 18 are significantly faster, have larger somas, and have stronger nonlinearities than Y cells projecting to area 17 (Boyd et al. 1998; Garey et al. 1967, 1977; Gilbert and Kelly 1975; Holländer and Vanegas 1977; Humphrey et al. 1985b; Mitzdorf and Singer 1978; Niimi and Sprague 1970). Fourth, Y\textsubscript{C} cells bifurcate into areas 17 and 18 more frequently than Y\textsubscript{A} cells (Bullier et al. 1984; Geisert 1980; Humphrey et al. 1985b).

Although it has been repeatedly shown that Y geniculate cells project to area 17 (Alonso et al. 2001; Boyd and Matsubara 1996; Bullier et al. 1979, 1984; Ferster and LeVay 1978; Freund et al. 1985a,b; Garey and Blakemore 1977; Gilbert and Wiesel 1979; Holländer and Vanegas 1977; Humphrey et al. 1985a,b; LeVay et al. 1976, 1977; Leventhal 1979; Tanaka 1983), careful experiments using both intracellular recordings and stimulus–response analysis have reached a different conclusion: the Y projection to area 17 is functionally very weak (Ferster 1990a,b). Consistent with this conclusion are the following findings. 1) Geniculate cells projecting to area 17 have slower conduction velocities and higher thresholds to electrical stimulation than geniculate cells projecting to area 18 (Ferster 1990a,b). 2) The linearity of spatial summation is “Y-like” for most area 18 cells and “X-like” for most area 17 cells (Ferster and Jagadeesh 1991; Movshon et al. 1978b; Spitzer and Hochstein 1985). 3) On average, receptive fields are three times larger in area 18 than area 17, exactly the same 3:1 ratio of Y:X retinal ganglion cells (Ferster 1981; Movshon et al. 1978a; Pollen and Ronner 1975; Shapley and Lennie 1985; Troy 1983).

The different opinions about the functional significance of the Y pathway in area 17 could be easily reconciled by accepting the existence of two different Y channels. Because most inputs to area 17 originate in Y\textsubscript{A} cells and X cells, it is not surprising that the bulk of the geniculate input to area 17 has low conduction velocity (Ferster 1990b; Humphrey et al. 1985a; Mitzdorf and Singer 1978; if we assume that receptive-field size and conduction velocity are correlated). It is not surprising either that most area 17 cells have X-like linearity of spatial summation because, at least near the area centralis, area 17 cells are 4 times more likely to receive input from an X cell than from a Y cell (Alonso et al. 2001). Moreover, for those cells receiving mixed Y\textsubscript{A} and X\textsubscript{A} input (Alonso et al. 1996; Ferster 1990b; Tanaka 1983), the weak nonlinear contribution from the Y\textsubscript{A} cells could be easily washed out by the more abundant X input. Finally, although receptive fields are 3 times larger in Y than in X retinal ganglion cells (see Shapley and Lennie 1985 for review), the ratio is <2 for Y\textsubscript{A}/X\textsubscript{A} geniculate cells and is only near 3 for Y\textsubscript{C}/X\textsubscript{A} cells (see RESULTS). In fact, the ratio of receptive-field sizes between area 17 cells located at the top (Y-recipient) and bottom of layer 4 (X-recipient) is <2 (Tolhurst and Thomson 1981).

The existence of subcategories within the X and Y pathways is unlikely to be an oddity of the cat visual system. In primates X cells are found in both the parvocellular and magnocellular layers of LGN (Kaplan and Shapley 1982) and their properties may not be the same across layers (e.g., X-parvocellular cells may have smaller receptive fields and slower response time courses than those of X-magnocellular cells). There are data suggesting that different morphological types of X cells may coexist within a single geniculate layer (Friedlander et al. 1981; see also Dacey et al. 2003), and some authors have reported subcategories of lagged and nonlagged cells within the X and Y pathways (Humphrey and Weller 1988; Mastrokareta et al. 1987, 1991).

The Y visual pathway was probably designed to detect rapid changes in the environment (Paternak and Maunsell 1992; Tolhurst 1973); however, change is important for both motion and shape processing. Therefore two specialized Y channels may be needed for vision in the cat. In the motion channel, the fast Y\textsubscript{C} cells with their large receptive fields could provide excellent temporal resolution for the rapid detection of a visual stimulus. In the shape channel, the slower Y\textsubscript{A} inputs with their smaller receptive fields could provide a fair compromise between the temporal and spatial resolution needed for the rapid identification of the stimulus shape. The idea of 2 separate Y channels can be traced back to the work of Mitzdorf and Singer (1978). Future studies will probably reveal an increasingly larger number of channels that originate at different levels within the visual pathway (Yabuta et al. 2001).

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DISCLOSURES

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