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# Effect of Background Colors on the Tuning of Color-Selective Cells in Monkey Area V4

Makoto Kusunoki, Konstantinos Moutoussis, and Semir Zeki

Wellcome Laboratory of Neurobiology, University College London, London, United Kingdom

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**Makoto Kusunoki, Konstantinos Moutoussis, and Semir Zeki.** Effect of background colors on the tuning of color-selective cells in monkey area V4. *J Neurophysiol* 95: 3047–3059, 2006; doi:10.1152/jn.00597.2005. When objects are viewed in different illuminants, their color does not change or changes little in spite of significant changes in the wavelength composition of the light reflected from them. In previous studies, we have addressed the physiology underlying this color constancy by recording from cells in areas V1, V2, and V4 of the anesthetized monkey. Truly color-coded cells, ones that respond to a patch of a given color irrespective of the wavelength composition of the light reflected from it, were only found in area V4. In the present study, we have used a different approach to test the responses of V4 cells in both anesthetized and awake behaving monkeys. Stimuli of different colors, embedded within a Mondrian-type multicolored background, were used to identify the chromatic selectivity of neurons. The illumination of the background was then varied, and the tuning of V4 neurons was tested again for each background illumination. With anesthetized monkeys, the psychophysical effect of changing background illumination was inferred from our own experience, whereas in the awake behaving animal, it was directly reported by the monkey. We found that the majority of V4 neurons shifted their color-tuning profile with each change in the background illumination: each time the color of the background on the computer screen was changed so as to simulate a change in illumination, cells shifted their color-tuning function in the direction of the chromaticity component that had been increased. A similar shift was also observed in colored match-to-sample psychometric functions of both human and monkey. The shift in monkey psychometric functions was quantitatively equivalent to the shift in the responses of the corresponding population of cells. We conclude that neurons in area V4 exhibit the property of color constancy and that their response properties are thus able to reflect color perception.

## INTRODUCTION

Perhaps the most striking characteristic of the organization of the visual cortex is its functional specialization, by which we mean that different attributes of the visual scene, among them color, are processed by anatomically separate and functionally specialized systems (Livingstone and Hubel 1988; Zeki 1978; Zeki et al. 1991). Functional specialization is also reflected in the temporal perceptual dimension because different attributes of the visual scene are perceived asynchronously, color being perceived before motion and form (Arnold et al. 2001; Moutoussis and Zeki 1997a,b). The notion of a cortical specialization for color should in fact have been hinted at before these discoveries, through the clinical studies of a patient with acquired color vision defects after lesions in the lingual and fusiform gyri (Verrey 1888). But this evidence was rapidly

dismissed by Salomon Henschen and by Gordon Holmes (see Zeki 1990 for a review) because Verrey, without explicitly saying so, had implied that the primary visual receptive center in the brain was not restricted to the calcarine (striate) cortex, as supposed by Henschen and Holmes, and that part of it was specialized for color. The notion of a color specialization in the brain was therefore effectively lost from sight for well over 70 years (see Damasio et al. 1980; Zeki 1990 for reviews). It was only after the direct physiological demonstration of a specialization for color and for visual motion in areas V4 and V5 of monkey extrastriate cortex (Zeki 1973, 1974), respectively, that the idea of a color center in the brain, outside of and distinct from V1, was established. Further confirmation of the central role area that V4 plays in color vision came from anatomical studies in the monkey (DeYoe and Van Essen 1985; Shipp and Zeki 1985; Zeki and Shipp 1989) as well as from imaging studies in both the human (Lueck et al. 1989; McKeefry and Zeki 1997; Wade et al. 2002; Zeki et al. 1991) and the monkey (Wade et al. 2003). In spite of what we consider to be formidable evidence in favor of a functional specialization in the primate visual brain, there is an alternative view of its organization, with which we disagree, namely that all visual areas, far from being specialized, are in fact multipurpose and that there is therefore no specialization for color or any other visual attribute in the brain at all (for reviews, see Schiller 1996, 1997).

The most important characteristic of the color system is color constancy—the fact that the color of surfaces remains largely unaltered in spite of wide fluctuations in the wavelength-energy composition of the light reflected from them. The precise strategy that the brain uses to generate constant colors is not known, and several alternatives have been suggested. Whatever the implementation strategy may be, it must involve a comparison of the amounts of long-, middle-, and short-wave light reflected from one surface and from surrounding surfaces (Land 1974; Land and McCann 1971). Psychophysical, imaging and electrophysiological evidence suggests that such a comparison is shared between early and late stages of the visual pathway (Bartels and Zeki 2000; Moutoussis and Zeki 2000). Physiological evidence shows that cells whose responses correlate with color as perceived by humans, rather than the wavelength composition of the stimulus, occur in area V4 but not V1 (Zeki 1983; but see also Wachtler et al. 2003 and DISCUSSION). Wavelength-selective cells of the latter area (and some V4 cells) were found to respond to an area of any color as long as it reflected a sufficient amount of light of their

Address for reprint requests and other correspondence: S. Zeki, Wellcome Laboratory of Neurobiology, University College London, London WC1E 6BT, UK (E-mail: zeki.pa@ucl.ac.uk).

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preferred wavelength and lesser amounts of the other two wavelengths. Some V4 cells, on the other hand, responded to an area of their preferred color irrespective of the wavelength composition of the light reflected from it and did not respond to areas of other colors even when they were reflecting light of the same wavelength composition as the area of their preferred color (Zeki 1983). Cells at even more central stations differ from those in V1 in having narrower and nonlinear tuning contours (Hanazawa et al. 2000; Komatsu et al. 1992). In the present study, we wanted to verify these previous findings in the ventral part of V4, between the lower bank of the inferior occipital sulcus and the collateral sulcus. In addition to recording from anesthetized animals, we also recorded from trained awake behaving monkeys so that we could correlate directly neuronal activity with the animals' perception rather than rely solely on our own perceptual experience. Our quantitative neuronal and psychophysical results confirm previous findings (Zeki 1983), extend them to the ventral part of area V4, and allow for a more precise assessment of the relationship between cell properties in V4 and the perception of color.

## METHODS

### Animals

Four male cynomolgus monkeys (*Macaca fascicularis*) weighing between 1.5 and 2.5 kg were used for the anesthetized experiment and two male rhesus monkeys (*Macaca mulatta*) weighing 5.0 kg for the awake experiment. Animal care and use were in accordance with the United Kingdom Animals (Scientific Procedures) Act. All experimental procedures were approved by the ethical committee of University College London and done under licenses from the U.K. Home Office.

### Anesthetized experiment

Anesthesia was induced with an intramuscular injection of ketamine and maintained by a continuous intravenous administration of propofol, sufentanil citrate, pancuronium bromide, and dexamethasone in glucose saline. In later experiments, anesthesia was maintained with halothane in O<sub>2</sub>-N<sub>2</sub>O instead of propofol. Blood pressure, rectal temperature, heart rate, and end-tidal CO<sub>2</sub> were monitored throughout the experiment. The rest of the surgical procedure, as well as the recording ones, are as described in previous papers (Moutoussis and Zeki 2002).

### Awake experiment

Monkeys were first trained to sit in a primate chair and accept food and liquid in it. Under general ketamine/propofol anesthesia, each animal was subsequently implanted with a plastic head holder for restraint of the head during recordings, and two plastic recording cylinders were placed over the prestriate area of each hemisphere. The implants were anchored to plastic and stainless steel screws fixed to the skull with acrylic resin. The animals were allowed to recover fully from surgery before any experimentation and their weights and health were regularly monitored. They were otherwise housed together in a large cage and allowed unlimited access to water for  $\geq 48$  h every weekend.

### Visual stimulation

All visual stimuli were presented on a CRT computer monitor (Sony Multiscan 20seII). The distance of the monitor from the animals was 32 cm in the awake experiments and 60 cm in the anesthetized ones. The monitor was 38 × 29 cm, so the screen covered a visual angle of  $\pm 30^\circ$  horizontally and  $\pm 24^\circ$  vertically in the awake experiments. Stimulus presentation and behavioral paradigms were controlled by a personal computer running the REX data-acquisition language under the QNX

real-time operating system. In the anesthetized experiment, the CRT monitor mounted on a lift with casters was placed to cover the receptive field of the recording neuron. In the awake experiment, stimuli were presented while the animal was fixating a small spot at the center of the CRT monitor. The colors of stimuli were calibrated with a spectrometer (Photo Research, Spectra Scan PR 650) to reproduce the color according to the coordinates in the CIE chromaticity diagram. We measured the CIE XYZ values for the individual R, G, and B phosphors at 16 of the 256 level calibration points and estimated the CIE XYZ for any of the 256 R, G, and B levels by using spline interpolation. Peak wavelengths of blue and green phosphors were 448 and 532 nm, respectively. The red phosphor had two peaks at 628 nm (primary) and 704 nm (secondary). We then added the XYZ for the red, green, and blue values to create color stimuli corresponding to particular coordinates in the CIE (1931) chromaticity diagram (details can be found in the APPENDIX of Bartels and Zeki 2000).

### Receptive field plotting

The relationship between stimulus and receptive field size was crucially important for this study and therefore required special precautions. First, we used a patch of various colors or a slit of various orientations as a probe and moved them manually using a joystick to find the conventional excitatory receptive field and the preference of the cell. If the cell showed a preference for a particular color, we plotted the outer border of the excitatory receptive field with a probe of that color. Then we determined the size of the stimulus so that it covered the entire receptive field, and we measured the color selectivity of the cell using a black background (CIE chromaticity coordinate:  $x = 0.3487$ ,  $y = 0.3265$ ,  $Y = 0.0110$ ). If the cell showed any selectivity with this test, it was also tested with the multi-colored background, its excitatory receptive field now consisting of a black patch only. If it showed an excitatory response under this condition, we increased the size of the stimulus and tested again and also made sure that the response to the color-patch alone did not deteriorate, since V4 is known to have a suppressive surround of the same color-preference as the center (Shein and Desimone 1990). Once we found a neuron that was stable and showed a preference for color, we carried out the following tests.

### Color-tuning tests

We used either 7 or 15 different isoluminant colored stimuli [ $3.7181 \pm 0.1249$  (SD)  $\text{cd/m}^2$ ] to examine the color preferences of cells in greater detail. The colors used to test each cell are plotted in the CIE chromaticity diagram (Fig. 1A). The triangle indicates the area of CIE coordinates that could be displayed on our computer screen. To test the preference of each cell, a rectangular stimulus of each color covering the excitatory receptive field was presented in random order for 1 s against a black background. To test the tuning of each cell's response between the green and red (G-R tuning) or yellow and blue (Y-B tuning) axes in more detail, further color stimuli along the line between the two colors in the CIE chromaticity diagram were used. The coordinates of the endpoints of the lines were red (0.4706, 0.2530), green (0.2412, 0.4362), blue (0.1507, 0.0643), and yellow (0.4537, 0.4753). The distance between the two colors was divided equally into 20 segments and 15 of them were used to record cells' responses. These stimulus sets were also used as cue stimuli for the color-discrimination task (see following text).

### Color-induction tests

A multi-colored Mondrian pattern with a rectangular black hole in its center was used as a surrounding background stimulus. The size of the surrounding stimulus was  $30^\circ \times 30^\circ$ , and the position and the size of the central black rectangle was adjusted to match the cells' receptive fields. In some experiments, smaller Mondrian patterns ( $5^\circ \times 5^\circ$ ) were distributed all over the CRT screen, and a black rectangle of the size of a stimulus patch was placed to cover a cell's receptive field. The wave-

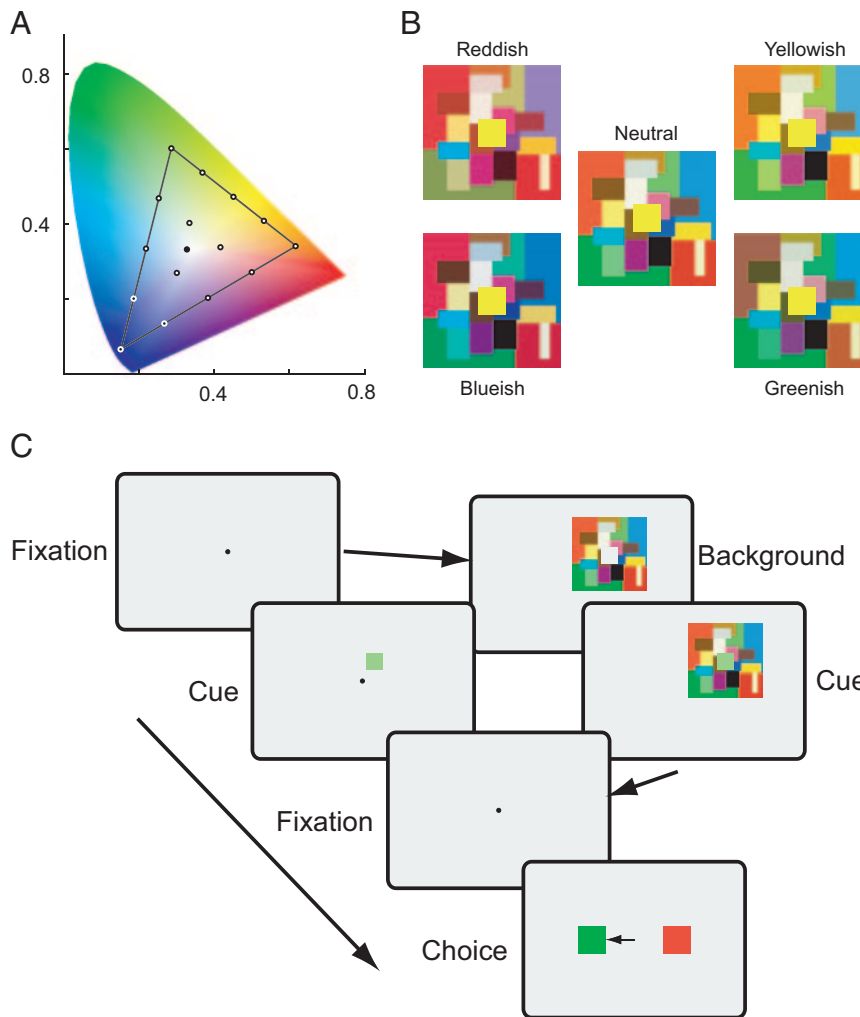


FIG. 1. *A*:  $x, y$  coordinates of the chromatic stimuli used in these experiments are plotted on the CIE chromaticity diagram. The colors shown here are approximations and may not accurately represent the actual ones used. *B*: illustration of the 5 different Mondrian illuminations used to test for color constancy. The size of the central square test patch was adjusted to the size of the neurons' receptive fields and, for each different background, was used to plot the color tuning of the cell. *C*: color perception training task: while the animal was fixating a central spot, sample stimuli with/without background were displayed on the monitor and, after a delay, 2 choice stimuli of red-green or yellow-blue were displayed. The animals were trained to saccade to the stimulus which looked similar to the sample stimulus.

length composition of each Mondrian patch was modified to simulate the light reflected from a set of colored papers (Color Aid) used in previous studies from our laboratory (Zeki 1983) (see Fig. 1*B*). In short, the surface reflectance of each patch for short, medium and long wavelength light was measured and the light reflected from the patch under an illuminant of different wavelength composition was calculated to simulate the color viewed under that illuminant (for details see Bartels and Zeki 2000). There were five different possible background illuminations: neutral (mean CIE  $x = 0.313, y = 0.326, Y = 2.33$ ), reddish (mean CIE  $x = 0.357, y = 0.277, Y = 1.86$ ), greenish (mean CIE  $x = 0.276, y = 0.372, Y = 2.84$ ), yellowish (mean CIE  $x = 0.420, y = 0.492, Y = 3.16$ ), and bluish (mean CIE  $x = 0.225, y = 0.188, Y = 1.52$ ). The same stimulus sets used in the color-tuning test were also used here as test stimuli. The Mondrian pattern with a black hole over the receptive field appeared when the monkey fixated the central spot in the awake experiment or at the beginning of each trial in the anesthetized experiment, and, after a delay of 500 ms, a colored stimulus appeared over the black central rectangle. After 1 s of stimulus presentation, both the stimulus and surrounding background disappeared, i.e., the background stimulus was present during the prestimulus period and stimulus presentation but not during intertrial (nonfixating) periods.

*Color-discrimination task*

Awake monkeys were first trained with a visual-fixation task and then a color-discrimination task. The animals' direction of gaze was monitored with an eye-tracking system using an infrared video camera (ASL: Model 500). The animals were first trained with a delayed

match to sample task. In this, a fixation spot appeared at the center of the screen and, while the animal was fixating within a  $1^\circ$  window, a para-foveal rectangular stimulus of green, red, yellow, or blue appeared for 1 s as a cue. After a random delay of between 0.5 and 1 s, matching stimuli of two of the four colors, including the same color as the cue, appeared on either side of the fixation spot. When the fixation spot disappeared 0.5–1 s after the appearance of the match stimuli, the animal had to choose the stimulus of the same color as the cue by making an eye movement toward it for liquid reward. After performance had reached  $>90\%$  success rate in this task, we started varying the color of cues between red and green or between yellow and blue (see color-tuning test), and animals were made to choose between the two respective colors. The match stimuli were presented randomly to the left or the right of the fixation spot. During the first stage of training, we used only highly saturated colors. Once the performance of the animals reached  $>90\%$ , we added unsaturated (grayish) cues and checked the performance of the animals to those grayish stimuli. The colors for which the animals' performance dropped to  $<75\%$  were defined as "neutral" colors, and the animals were rewarded randomly when those colors were presented as cues. To test the effect of colored backgrounds on the perception of color, cues were presented against Mondrian backgrounds of various illuminations (see Fig. 1*C*).

*Physiological methods*

During a recording session, the anesthetized animals were paralyzed and faced a tangent screen 60 cm away. The awake animals sat

in a primate chair with head restrained and faced a CRT monitor but were otherwise free to move their arms and legs. Single units were recorded using a tungsten microelectrode (FHC) controlled by a microdrive system. Electrodes were introduced into the cortex through a stainless steel guide tube held in place by a plastic grid containing holes spaced at 1-mm intervals. Unit discharges were detected by a time window discriminator (Nihon Kohden) and, once isolated, were sampled at a rate of 1 kHz by the computer. In the awake experiments, horizontal and vertical eye position signals were sampled at a rate of 50 Hz. The response of the recorded neuron was monitored on-line with a raster display and stored on magnetic disk for off-line analysis.

### Data analysis

We used MatLab (Mathworks) for analysis of most of the cells' response. The number of spikes at 950-ms intervals, from 50 ms after stimulus onset to its end, were counted and characterized the response of the cell. A two-way ANOVA was used to test for statistical significance between any differential responses of neurons with respect to central and background illuminations. To further quantify the strength of neuronal tuning with respect to the chromatic properties of the central stimulus, we used the following color index:  $CI = (R_{\text{best}} - R_{\text{null}})/(R_{\text{best}} + R_{\text{null}})$ , where  $R_{\text{best}}$  is the response to the best color patch in the color selectivity test and  $R_{\text{null}}$  is that to the color patch yielding the lowest response. We classified a cell as color selective if its responses to different color stimuli varied ( $P < 0.01$ ) and CI was larger than 0.33, i.e.,  $R_{\text{best}}$  was larger than twice  $R_{\text{null}}$ . To visualize the color tuning of each neuron, the average response to each color was plotted on the CIE chromaticity diagram as the radius of a circle centered on the particular color (bubble plots). We also plotted iso-firing rate contour lines on the CIE chromaticity diagram using triangle based cubic interpolation of the responses to test patches based on the Delaunay triangulation. To estimate the R-G or Y-B tuning of the neurons that were not tested with these tuning tests, the sections of the interpolated firing rate between these colors were used. In quantifying the color induction effects, we fitted Gaussian or binominal curves to the chromaticity tuning data, and tested their relationship to detect any shifts. Similarly, psychometric data for each different background illumination was fitted with binomial curves, and the effects observed compared with the neuronal data.

### Model analysis

The responses of color-selective cells were classified according to the fits to four models. Mostly, we followed the method of Hanazawa et al. (2000) and modified type 3 and type 4. We used the following models for CIE coordinates

$$R = a_1x + a_2y + a_3$$

$$R = a_1 \tanh(a_2x + a_3y + a_4) + a_5$$

$$R = a_1 \tanh\{[a_2(x - 0.3333) + a_3(y - 0.3333) + a_4] - [a_3(x - 0.3333) - a_2(y - 0.3333)]^2/a_5^2 + a_6$$

$$R = a_1 \tanh\{-[a_2(x - a_7) + (1 - a_2)(y - a_8)]^2/a_3^2 - [(1 - a_2)(x - a_7) - a_2(y - a_8)]^2/a_4^2 + a_5\} + a_6$$

where  $R$  is the neuronal response,  $x$  and  $y$  are the chromaticity coordinates in the CIE chromaticity diagram, and  $a_1, a_2, \dots, a_8$  are regression coefficients. Type 1 and 2 models have linear response contours with wide tuning, whereas types 3 and 4 have nonlinear response contours with narrow tuning. The new free parameters  $a_7$  and  $a_8$ , added here in the type 4 model, could increase its fitting power and thus might result in some bias toward type 4 classification. The regression coefficients of each model were determined by the least-squares method, and the quality of fit was evaluated using a statistical criterion (ANOVA,  $P < 0.001$ ). If this criterion was not reached by

any model, the neuron was labeled as unclassified; if reached by more than one model, the goodness of fit to each model was compared by calculating the Bayesian information criterion (Schwarz 1978) from which the most appropriate model was determined. Type 1, 2, and 4 models and a modified type 3 model were also used for the MacLeod-Boynton (MB) chromaticity diagram (MacLeod and Boynton 1979). Type 3 as used for the MB coordinate is

$$R = a_1 \tanh[(a_2p + a_3q + a_4) - (a_3p - a_2q)^2/a_5^2 + a_6$$

where  $p$  and  $q$  are the chromaticity coordinates in the MB chromaticity diagram.

### Histological methods

At the termination of the experiment, animals were deeply anesthetized with sodium pentobarbital and then perfused through the heart, first with heparinized saline and then with 4% paraformaldehyde in 0.1 M phosphate buffer (pH 7.4), followed by 10, 20, and 30% sucrose in phosphate buffer. The brain was subsequently cut, and every 50- $\mu\text{m}$  section through the region of interest was saved and stained for Nissl substance with cresyl violet to show the electrode tracks in the cortex. The tracks were found to be within the upper and lower banks of the inferior occipital sulcus, corresponding to the lower portion of V4 and representing the upper contralateral quadrant of the visual fields.

## RESULTS

### Color tuning

In total, we recorded from 59 single units in ventral V4 (15 from awake monkeys and 44 from anesthetized monkeys), mainly between the lower bank of the inferior occipital sulcus and the collateral sulcus—see Fig. 2C. Of these, 48 showed a statistically significant ( $P < 0.05$ ) preference in their responses to different color patches, and in 45 (15 from awake monkeys and 30 from anesthetized monkeys), the CI was large enough ( $>0.4$ ) to merit more detailed study (see METHODS). Eleven of 15 cells from awake monkeys were tested in color-discrimination tasks and 7 were also tested with different backgrounds. Their receptive fields ranged from  $1^\circ \times 1^\circ$  to  $14^\circ \times 14^\circ$  in size and from  $0^\circ$  to  $39^\circ$  in eccentricity. An example of a color-selective neuron is shown in Fig. 2A. When tested with different isoluminant colors against a black background, it showed a clear preference for bluish stimuli. The distribution of response preferences along the CIE (1931) chromaticity diagram for all such selective neurons is shown in Fig. 2B. The best and the second best colors for each cell were determined. Many cells had prolonged excitatory regions in color space, with two or more peaks. But with a few exceptions, these peaks were usually not separated by nonresponsive colors. As a population, the preferred colors of V4 cells covered almost all the tested CIE regions. We have compared color indices, maximum firing rates and background firing rates between anesthetized and awake behaving animals. With color indices, no statistically significant difference ( $P = 0.47$ ,  $t$ -test) was found between awake (mean = 0.67) and anesthetized animals (mean = 0.62). In contrast to the color indices, maximum responses (mean: 52.7 in awake, 31.1 in anesthetized,  $P = 0.02$ ) and background activities (mean: 16.2 in awake, 8.4 in anesthetized,  $P = 0.008$ ) differed significantly between the two conditions.

Tuning properties of V4 cells are shown in Fig. 3. Bubble plots of the strength of responses, together with contours

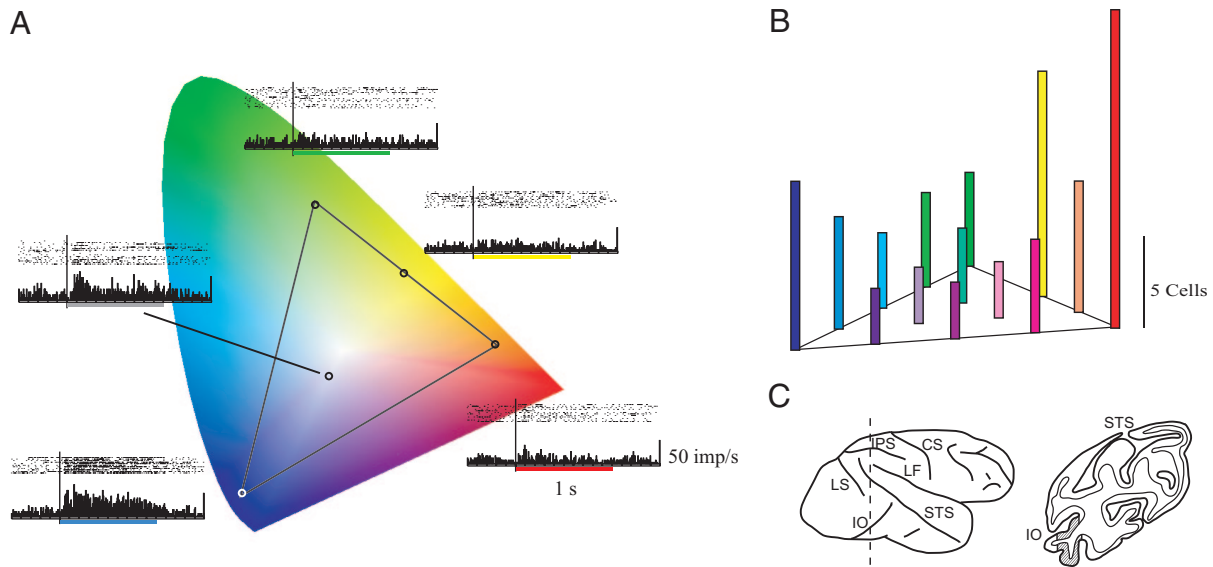


FIG. 2. *A*: example of the responses of a neuron in area V4 to patches of different isoluminant colors presented against a gray background. Spike rasters and response histograms are plotted with reference to the CIE chromaticity diagram. The bar under each histogram shows the duration of stimulus presentation (1 s). The neuron responded best to the blue stimulus. *B*: histogram showing the distribution of spectral preferences of all the V4 neurons recorded in these experiments. *C*: schematic representation of the part of the brain from which recordings were made. The dashed line on the lateral view of the monkey brain shows the approximate position of the coronal section (*right*). ▨, spectrally tuned neurons.

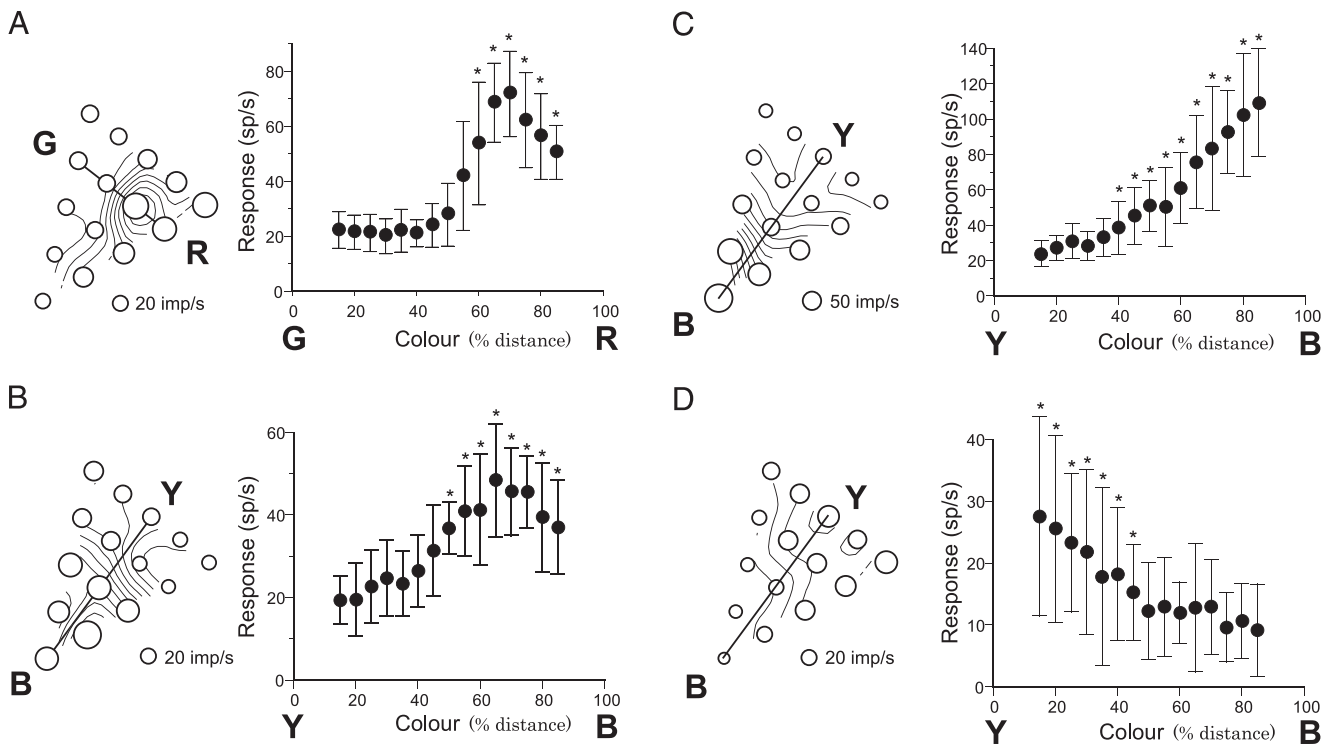


FIG. 3. Bubble and contour plots of neural responses across the CIE chromaticity diagram (*left*), together with more detailed color-tuning curves along particular directions of color space (*right*) for 4 different V4 neurons (*A–D*). The size of each bubble represents the magnitude of the cell's response to the color at each position in the CIE chromaticity diagram. Contour lines connect color space points eliciting the same neural response. Straight lines in the bubble plots show the color-space direction used for plotting the more detailed color-tuning curves. The responses to 15 equally distributed color patches along the line were recorded and plotted against percent distance of test colors between green (G) and red (R) or yellow (Y) and blue (B). The neurons in *A* and *B* showed a peak response inside the tested color space, whereas those in *C* and *D* did not. *Right*: error bars show SEs and \* shows significance with respect to the lowest response ( $P < 0.005$ ). *A*, *B*, and *D*: cells from awake monkeys tested in the color discrimination task. *C*: a cell from an anesthetized monkey.

connecting color points that resulted in identical neuronal firing rates are presented on top of the CIE chromaticity color-space. For a more detailed picture of the tuning of the cells, the responses of each cell to 15 equally distributed color stimuli along the line G-R in Fig. 3A, and Y-B in Fig. 3, B, C, and D, are shown to the right of each panel (G-R tuning and Y-B tuning, see METHODS). Some neurons had a sharp peak in their selectivity, whereas others showed a broader tuning profile. In addition, some neurons had their peak response well inside the color space triangle along which they were tested, whereas others had their maximum response near its edges (the latter probably had the preferred color-points outside the region over which we tested). This variability of tuning profiles can also be seen in the tuning curves to the right. As is evident from the bubble and contour plots, neurons in Fig. 3, A and B, showed a maximum response in the pink and purple regions of the color space. About 40% of the recorded V4 color-selective cells had the peak of their chromaticity tuning inside the tested color space. Neurons in Fig. 3, C and D, had maximum responses at the edge of the test area and probably would have peak responses outside the test area. About 60% of the recorded cells had their peak of color tuning on the edges of the tested color space.

#### Color induction

To test the effect of the background's chromaticity on the response of color-selective V4 neurons, we plotted their CIE tuning curves with different backgrounds, thus simulating different illumination conditions. As the background illumination changes, so does the color of the target inside the cell's

receptive field. A cell coding for color should therefore modulate its firing rate in response to changes in background illumination. This is not so for a cell that codes for the wavelength composition of the light reflected from the stimulus inside its receptive field because the latter never changes under these conditions. Hypothetically, under our testing conditions, a real color-constant cell should shift its tuning function toward the chromaticity of the light that has been increased in the background illumination. When, for example, the background alone is made more reddish, any target that it surrounds appears less reddish, and therefore needs more long-wave (red) illuminant to appear as red as before.

Figure 4 shows typical examples of the shift in the color-tuning curves of V4 neurons in the awake monkey. When stimuli were presented against a Mondrian background illuminated by a neutral (white) illuminant, the neuron in Fig. 4A gave its peak response to a bluish-purple stimulus (*middle*). When a yellowish background illumination was used instead, the neuron's peak shifted toward yellow (*right*). On the other hand, when a bluish illuminant was used to illuminate the background Mondrian, the neuron almost ceased responding, presumably because the tuning function shifted toward blue and the peak color response now lay outside the color-space used (*left*). Figure 4B demonstrates this effect more clearly by taking the yellow-blue line across CIE space and interpolating the responses: when yellow light is added to the background, the tuning curve shifts to the right (i.e., toward the yellowish part of the color space) and when blue light is added, the tuning curve shifts to the left (i.e., toward the bluish part of the color space). This cell behaved slightly erratically because, in addition,

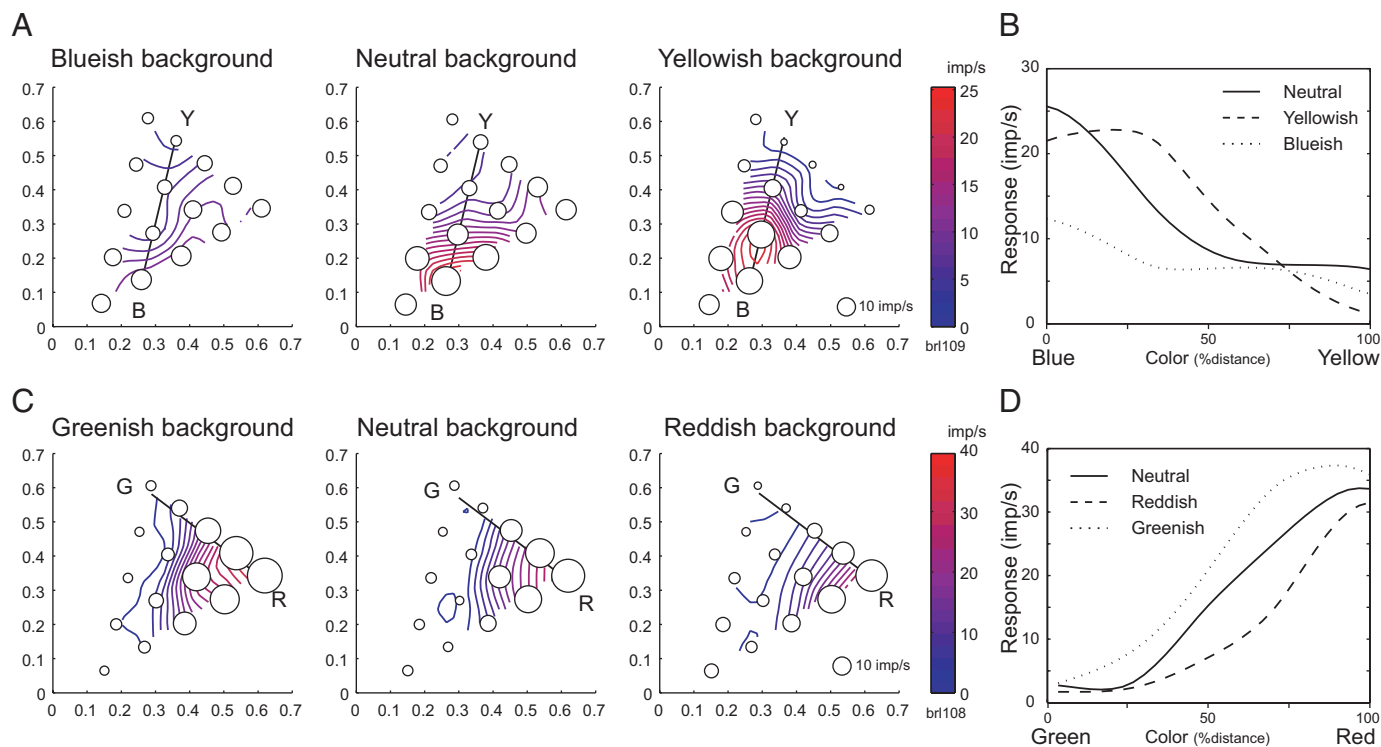


FIG. 4. Bubble and contour plots showing the effect of different background illuminations on the responses of a blue-purple (A) and a red (C) neuron to different colors across the CIE chromaticity diagram, together with interpolated tuning curves along their respective lines of maximal modulation in color space (B and D). Both neurons shift their response curves toward the color of the increased wavelength in the background illumination, thus reflecting the psychophysical effect that this increase has in color perception.

tion to shifting its responses toward another part of the spectrum, it also decreased the strength of its maximum response. Another example is shown in Fig. 4, *C* and *D*: a neuron preferring red under a neutrally illuminated Mondrian background shifts its curve toward green when a greenish Mondrian background is used instead (left), and toward red when a reddish Mondrian background is used. The interpolation in Fig. 4*D* demonstrates a clearer, more symmetrical effect than in Fig. 4*B*. Among other reasons, it could be that the chosen color-space line represents the preferred direction of cell's modulation better in one case than in the other. Often the shift of the tuning curve was away from the tested color space or the modulation effect was stronger in line points toward the neuron's preferred color. Because this is where the cell responds best, it is harder to see an effect toward the end of the nonpreferred color, where the response of the cell was much weaker. The neural effect is thus not always as symmetrical as one might expect, judging from the perceptual effect (see following text). Similar background effects to the one shown here were obtained in 71% of the V4 neurons tested (2-way ANOVA,  $P < 0.01$ ).

#### Model fitting

To classify the tuning of V4 color-selective cells in the CIE chromaticity diagram, the responses of 43 cells were fitted with four models. We often observed that the tuning behavior of cells changed when the background condition changed, which in turn affected classification of the cells into one of the four types. In those cases when a cell could be classified into more than one category, the final classification given to it was that of the highest category into which it had been classified. Figure 5 shows examples of the tuning types. Cells classified as type 1 and 2 (Fig. 5, *A* and *D*) had linear response contours and wide color tunings. Those classified as type 3 and 4 (Fig. 5, *B* and *E*) had curved (nonlinear) response contours and narrow color tunings. Cells classified as types 1–4 were 2 (4.7%), 6 (14.0%), 10 (23.3%), and 19 (44.2%), respectively. Six (14.0%) were labeled as unclassified. Some of type 3 and 4 neurons had a negative first coefficient ( $a_1$ ) and showed a trough within the chromaticity space (Fig. 5, *C* and *F*). Of 29 type 3 and 4 neurons, 7 (24%) showed this type of tuning. Shifts in tuning in response to different backgrounds were demonstrated clearly with the model analysis. Figure 5, *G* and *J*, *H* and *K*, and *I* and *L*, shows that the peak of the chromaticity tuning of a type 4 neuron shifted toward red when the background changed from greenish to reddish one. The estimated peaks ( $a_7$  and  $a_8$ ) outside the stimulus space [greenish background: (0.9290, 0.7690), neutral background: (0.6810, 0.3800), and reddish background: (0.7780, 0.1800)] and the amount of the shift projected on the axis of background change was 0.248 in total. The geometry of the tuning shift was not uniform over the CIE chromaticity diagram. It was often larger around the neuron's preferred color than around its nonpreferred color, when the background changed to its preferred and nonpreferred colors.

The responses of the cells were also fitted with the coordinates in the MB chromaticity diagram to examine if their chromaticity tuning can be explained by the linear summation of cone inputs. The cells classified as types 1–4 were 2 (4.7%), 11 (25.6%), 17 (39.5%), and 6 (14%), respectively. Seven (16.3%) were labeled as unclassified. Note that, because our

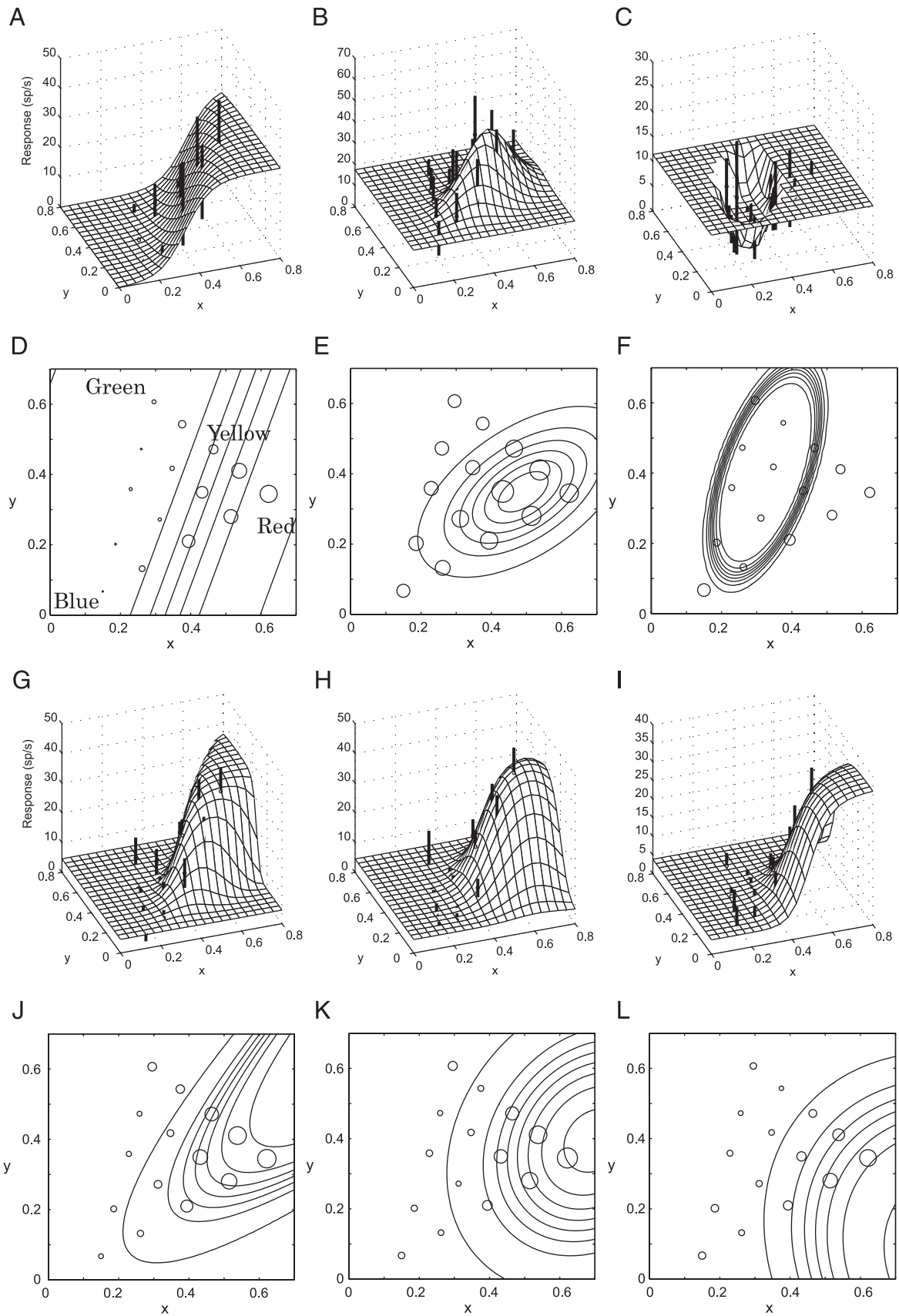
stimulus set was distributed within the CIE chromaticity diagram and not systematically distributed within the MB chromaticity diagram, the number of type 3 and 4 cells might be underestimated.

#### Monkey psychophysics

An advantage of the awake behaving monkey preparation was that, in addition to testing neurons in the way described above, we were also able to determine what the monkey was perceiving under our experimental conditions and thus relate directly the animal's perception to the firing of the cell under study. Before starting recordings, we tested the monkey's subjective perception of colors and color constancy using a color-discrimination task. Figure 6 shows the psychometric function of one monkey that had to decide whether a sample stimulus presented to him looked more reddish or greenish. The monkey's choice was nearly symmetrical around the 50% (gray) stimulus under the no background condition. Against a neutral background, the animal had a small tendency to choose more green, suggesting that our neutral background was slightly reddish. When the sample stimuli were presented against the reddish background, the psychometric function shifted toward red colors (compared with the neutral background condition), and the opposite was true when the sample stimuli were presented against the greenish background. Human control subjects showed steeper psychometric functions (not shown here), but the direction of the shift was the same as that in Fig. 6. We therefore conclude from these induction experiments that the monkeys were able to experience the color constancy effect that we ourselves were experiencing, as has been previously suggested (De Valois et al. 1974; Loop and Crossman 2000).

#### Single-unit activity during color-discrimination task

To compare directly the V4 neural activity with the monkey's color perception, we recorded single-unit activity while the animals were performing the color discrimination task. Figure 7*C* shows a monkey's psychophysical performance in a yellow/blue discrimination task during the recording of a neuron's activity. The resulting psychometric curves were noisier than the ones in Fig. 6, due to a smaller number of repetitions. With the neutral background, the monkey was at 50% choice for the yellowish stimulus, i.e., showed a bias toward choosing more blue. Also, the effect of the yellowish and bluish backgrounds was opposite and nonsymmetrical: the bluish background decreased the percentage of blue choices more in the gray-bluish range of test stimuli, whereas the yellowish background increased the percentage of bluish choices more in the yellowish range of test stimuli. The effect of each background is thus stronger for colors similar to it, bluish patches looking more yellowish under bluish background condition, and yellowish patches looking more bluish under yellowish background condition. The same is also true for changes in neuronal firing rate: since neurons are selective for particular color regions, any modulation observed might not be symmetrical throughout the range of tested colors. Figure 7, *A* and *B*, shows the responses of a V4 cell recorded during the same session. The cell preferred blue and did not show a peak in its response inside the range of tested colors.



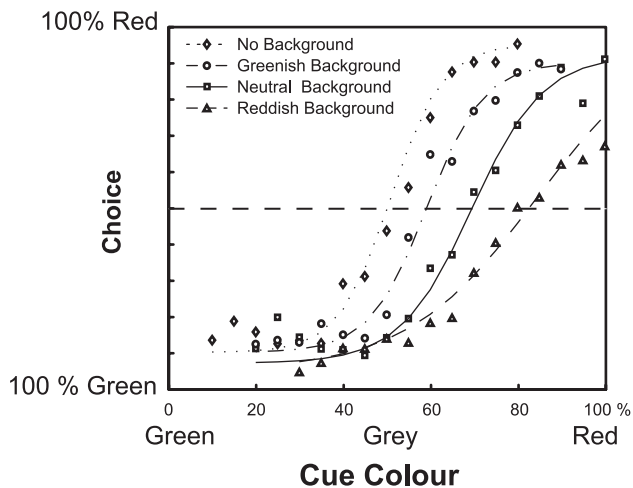


FIG. 6. Psychometric functions of a monkey's color perception under multi-colored Mondrian backgrounds of neutral, reddish and greenish illumination and no background conditions. Binomial curves are fitted to the original data. Fifteen different, equally distributed colored patches between green and red were used to plot the function in each case. Abscissa is percent distance between green (0%) and red (100%), which are illustrated as G and R in Fig. 3A, respectively. Horizontal dashed line indicates 50% choice level, i.e., the balance point in which colors did not look either more reddish or more greenish to the animal.

Histograms of the responses to the gray patch are shown in Fig. 7A as an example: under a yellowish background, when the gray patch appeared more bluish, the response was increased; the opposite was true with the bluish background. In general, as is evident in Fig. 7B, when the background was made more bluish (and thus all test colors appeared more yellowish), the responses of the cell to the different test colors decreased. This decrease was more pronounced in the gray-bluish part of the color line, i.e., the same part where the psychophysical effect of seeing less blue under a bluish background was also stronger. Similarly, making the background yellowish (and thus making test colors appear more bluish) increased the cell's responses. This increase was more pronounced in the yellowish part of the testing color range, i.e., the same part where the psychophysical effect of seeing more blue under a yellowish background was also stronger. Thus by comparing Fig. 7, B and C, one can see that the effect of changing background illumination is similar for the neuron and the monkey's behavioral performance.

#### Population analysis

To show that the findings described above do not represent single, isolated or exceptional cases, population results of the effect of color constancy on the responses of V4 cells are shown in Fig. 8. Twenty-five color-selective neurons successfully tested with 15 or 16 different colors under at least three different background illuminations were used. The ratio of neuronal responses using a background illumination opposite to each cell's preferred color ( $R_{non-pref}$ ) with respect to those under a background illumination similar to the preferred color ( $R_{pref}$ ) were plotted in Fig. 8A. To normalize the effects of

background illumination on the response to each test patch, modulation indices [ $MI = (R_{non-pref} - R_{pref}) / (R_{non-pref} + R_{pref})$ ] were calculated. The distribution of the difference in neuronal firing modulation indices under these two conditions is plotted in Fig. 8B. Both these figures include all color-selective neurons successfully tested and all tests made, i.e., also on neurons that did not show the modulation effect as well as color points where the effect was not very strong for the neurons showing the effect. In the majority of cases, the neuronal modulation reflects color perception: a greater response is given under the "nonpreferred" background, i.e., when the target colors are made to appear more "preferred," and vice versa. Figure 8C shows the population neuronal tuning functions of 15 neurons that showed a color tuning along the R-G or Y-B line. The neuronal responses were normalized with respect to the best response, aligned with respect to the best color under neutral background conditions and averaged. Such an analysis was necessary to compare quantitatively shifts in neuronal firing rate with shifts in monkey psychometric performance. When looking at single-unit responses, there wasn't always a good correspondence between the two. This was mainly because the psychometric functions were noisy; unlike one-dimensional psychometric functions, two-dimensional neuronal tuning functions were not linearly transformed when changing the background illumination, and the line in color-space of maximum modulation of the neuron did not always exactly correspond to the one that was tested psychophysically. To overcome these problems and see whether the shift of neuronal tuning can explain the shift of color perception, the population chromaticity tunings along the R-G line of eight cells, which had peak in R-G tuning and had been tested with reddish and greenish backgrounds, were calculated (as in Fig. 8C but for R-G cells only). The mean shift of these curves was then compared with the mean shift of the R-G psychometric functions shown in Fig. 6. Average distance of tuning curves at half height was 0.033 for the neuronal data and 0.029 for the psychophysical data, showing that the latter were accurately reflected by the former not only qualitatively but also quantitatively.

#### DISCUSSION

The colors that we perceive are not a simple function of the wavelength composition of the light reflected from objects. The brain's color system allows our perceived color of objects to remain stable despite changes in the wavelength composition of the illumination. It does so by comparing the wavelength composition of the light coming from one part of visual space with that coming from another. Such comparisons enable the brain to disregard changes in the wavelength composition of light coming from single surfaces and thus provide information about a constant property of surfaces and objects, namely their reflectance for light of different wavebands. Hence if the wavelength composition of light coming from the surrounds of an area changes, the color of the area will change as well (because its chromatic relationship with the surround

FIG. 5. Examples of model fitting in the CIE chromaticity diagram. A–F: examples of type 2, type 4 and type 4 inhibition cells are shown as surface plots (A–C, respectively) and contour plots (D–F, respectively). G–L: shift of tuning of a type 4 cell with greenish, neutral and reddish backgrounds shown as surface plots (G–I, respectively) and contour plots (J–L, respectively). In A, B, C, G, H, and I, empty circles, mean response to each stimulus and vertical bars indicate SEs. In D, E, F, J, K, and L, the size of each circle represents the magnitude of the cell's response to the color patch at each position in the CIE chromaticity diagram. The names of the colors are printed in D for reference.

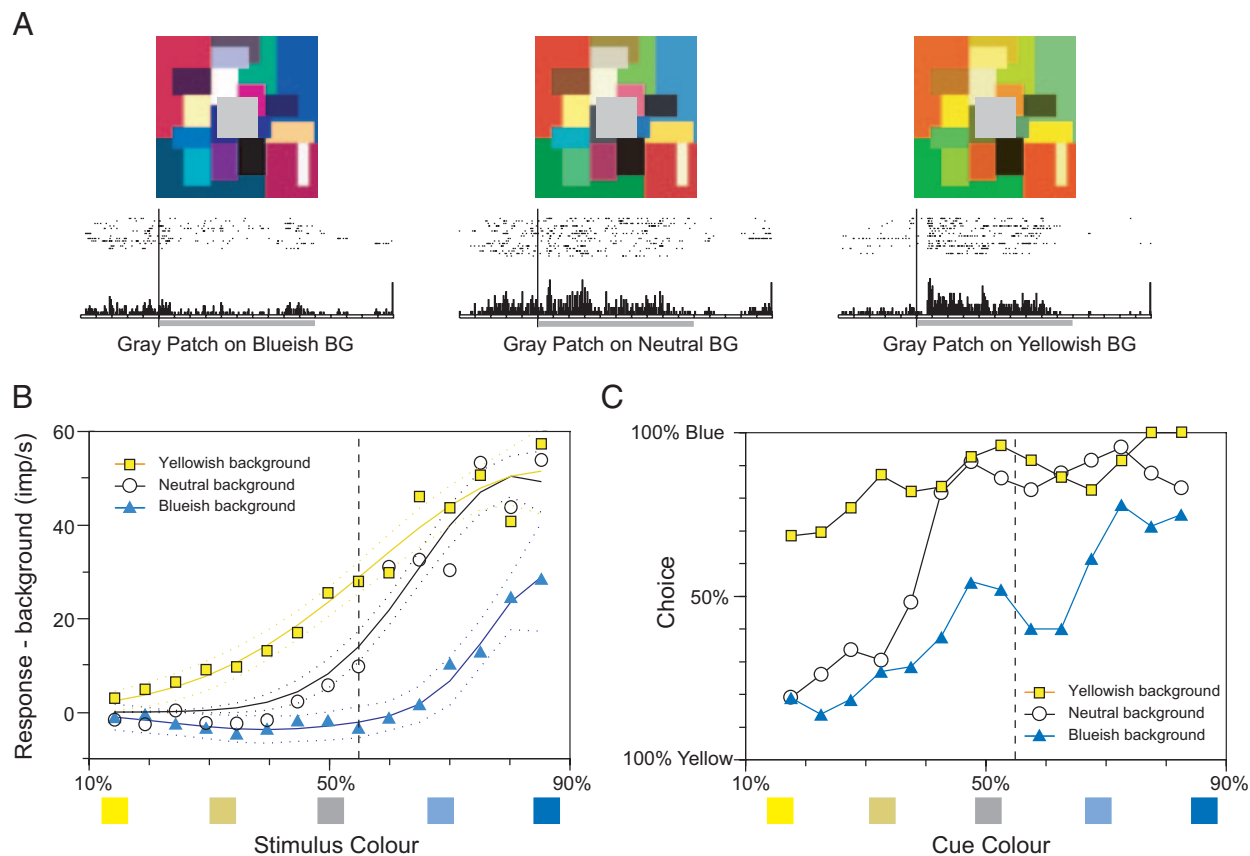


FIG. 7. An example of the effect of background illumination on the perception of the animal and the firing rate of a V4 neuron recorded from simultaneously. *A*: response of the cell to the gray test patch under a bluish (*left*) background is diminished, compared with the neutral (*middle*) background, whereas a yellowish (*right*) background enhances the response. *B*: responses of the same cell to different colors along the yellow-blue line in color space were fitted with binomial curves. Responses to most other colors decreased under the bluish background as well and increased under the yellowish background. Prestimulus activities varied during the recording session, so they were subtracted from the responses to clarify the shifts. *C*: color-discrimination psychometric curves of the monkey during the recording session shown in *B*. Vertical dashed lines in *B* and *C* indicate the gray patch shown in *A*. Abscissas of *B* and *C* represent the percent distance from the yellow stimulus to the blue stimulus illustrated in Fig. 3, *B–D*.

has changed), a phenomenon known as color induction. In the present study, we have used the latter method to show that the majority of cells in the ventral part of area V4 can code for the perceived color of objects.

#### Response of V4 color neurons

We recorded the responses of V4 color neurons to color stimuli corresponding to points in the CIE chromaticity diagram and examined their chromaticity tuning. Unlike most previous studies, we chose to record from the ventral part of area V4 for two reasons, one theoretical and one technical. Theoretically, there has been some argument as to whether ventral V4 subserves color and whether it is a separate area from dorsal V4 (Fize et al. 2003). We thus wanted to learn whether we would encounter color cells in the ventral extension of V4 and, if so, whether their responses would correlate with color or with wavelength composition. Technically, recording from deep in the sulcus provided stable single-unit activity for >1 hr, necessary to collect sufficient data under multiple background conditions. Our results show that cells in ventral V4 have similar color-selective properties as the ones in dorsal V4, suggesting that they are indeed subdivisions (upper and lower visual field representation) of the same cortical area (see also Wade et al. 2003).

We found various types of tuning, from planar ones to single-peak tuning with hue and saturation selectivity. This means that V4 carries various levels of information about color, from the degree of “redness” or “greenness” of a surface to its particular color. Komatsu et al. (1992) reported chromaticity tunings of color-selective cells in the inferior temporal (IT) cortex quite similar to those of our V4 cells. This suggests that the process of color perception starting from the retina is almost completed in V4 and that the information from V4 may be used in IT for further object recognition by combining it with signals related to other attributes such as shape. Komatsu et al. (1992) also reported the existence of color cells with multiple peaks. The responses of these cells are similar to the type 3–4 cells in V4 with negative  $a_1$ . The frequency of such cells in IT was 21.7%, and this is comparable with 24% in this study. Schein and Desimone (1990) reported that 28% of V4 cells had spectral-response curves with more than one peak. Although they did not test the response to saturation, their cells might belong to the same group recorded in this study.

An analysis of the responses of V1 and IT cells with model fitting by Hanazawa et al. (2000) showed that the frequencies of different types of color-selective neurons are remarkably similar in two areas (V1: type 1, 34.2%; type 2, 32.9%; type 3, 25.3%; type 4, 6.3%; IT: type 1, 20.5%; type 2, 43.6%; type 3,

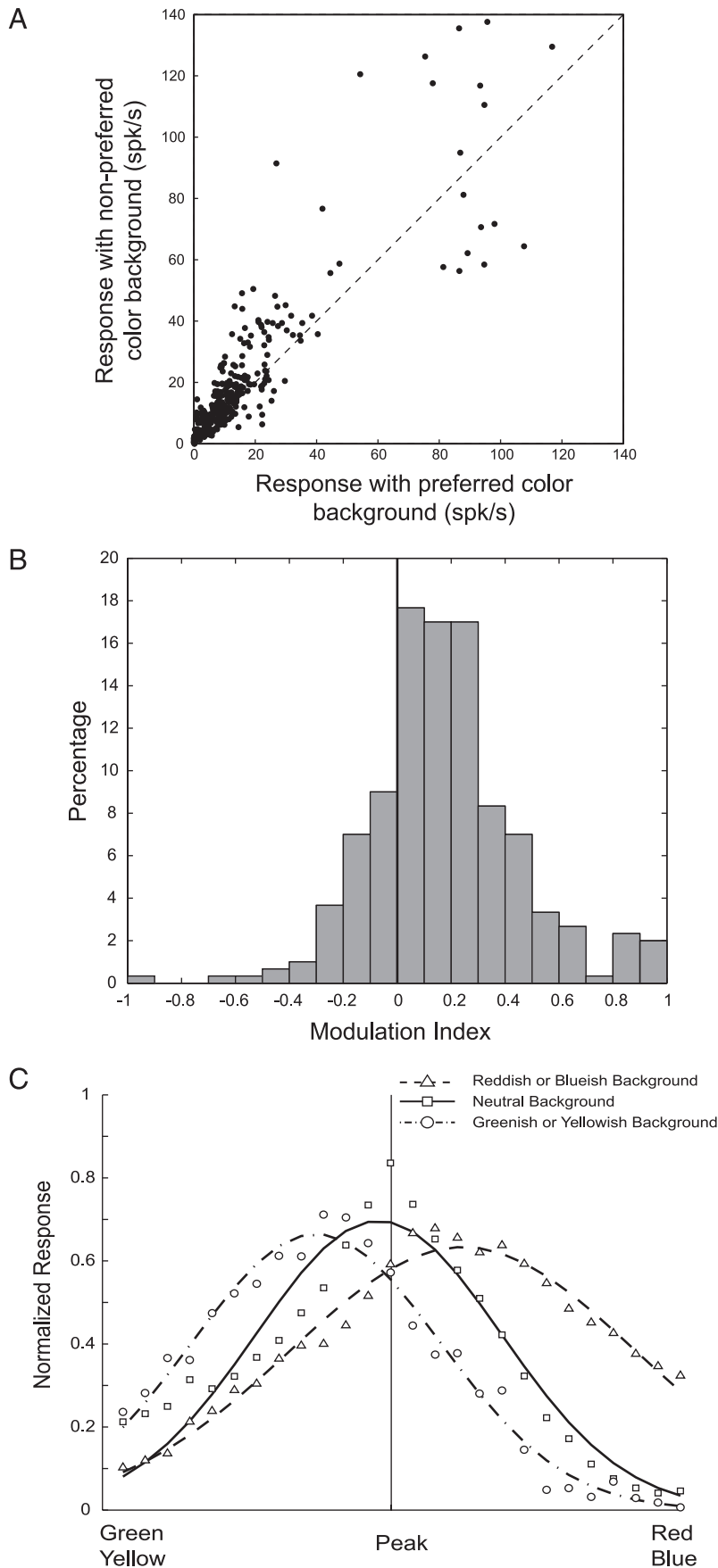


FIG. 8. Population results of the effect of background illumination on the responses of V4 neurons to different foreground colors. *A*: response of cells to a particular color patch under a background illumination which is opposite their preferred wavelength (ordinate) is plotted against the response to the same patch under a background illumination similar to their preferred wavelength (abscissa). Dotted diagonal represents a ratio of 1, i.e., equal responses. *B*: percent distribution of the modulation indices (see text). *C*: effect of background illumination on the population tuning. The responses of each cell along the color line of maximum modulation were normalized with respect to the best response, aligned to the response elicited by the best stimulus under neutral background, and averaged across the population. The averaged data were fitted with a Gaussian curve. The range of the color axis is 0.55 in CIE chromaticity scale, which is 1.3 times longer than the color axis we used for testing. The peak of the tuning curves under neutral background was often outside our tested region of color space, and therefore the average presented here appears sharper than the real tuning.

25.6%; type 4, 10.3%). The frequencies that we have obtained from V4 cells following a similar analysis were quite different (type 2, 4.7%; type 2, 25.6%; type 3, 39.5%; type 4, 14%). One of the major differences between our recordings and theirs was the existence of backgrounds in ours. When we re-classified the responses of 40 cells but this time using responses derived when there was no background, we obtained similar frequencies (V4: type 1, 7.5%; type 2, 40%; type 3, 30%; type 4, 5%). This suggests that (at least some) color cells change their tuning properties in the presence of surround stimuli.

#### *Shift of color tuning by multi-colored background*

In the present study, we varied the wavelength composition of the background illumination only, so that the wavelength composition of the light reflected from the area inside the cell's receptive field remained constant. But because of induction effects, the color of the latter area changed. In this way, instead of testing whether the response of the cell would remain the same under different illumination conditions, due to color constancy, we looked for any neuronal modulation that was consistent with the perceptual modulation resulting from manipulations in background illumination. We found that 71% of the color-selective neurons in ventral V4 modulated their firing rate in a way that reflects the psychophysical color constancy effects observed in both humans and monkeys. A similar result has been previously reported in dorsal V4 of anesthetized animals (Zeki 1983), using the equivalent method of testing directly for color constancy rather than color induction: this was done by changing the wavelength composition of the light coming from the entire scene. Although the wavelength composition of the light reflected from the area inside the cell's receptive field changed as well, its color remained the same.

For reasons explained in RESULTS, there was not always a good quantitative relationship between activity shifts of single neurons and psychophysical shifts of the animal's perceptual capacities during individual recordings. Because the monkey perception was noisy, we took the shift of the psychometric functions obtained over long periods of pure psychophysical testing to reflect the true value of the shift in color perception of the animal. When these shifts were quantitatively compared with the shifts in neuronal tuning functions of the corresponding neuronal population, the two were found to be of the same amount. This suggests that, at least under our stimulus condition, the shift in the chromaticity tuning of cells in V4 can account for the shift in color perception. We therefore conclude that cells in this area are able to signal real color, rather than simply the wavelength composition of the light reflected from inside their classical receptive field.

#### *Role of V4 in color perception*

The idea that color constancy is not achieved before reaching area V4 in the color pathway has been previously put forward, mainly due to the reported absence of any color-constant cells in either area V1 (Zeki 1983) or area V2 (Moutoussis and Zeki 2002), using methods similar to the ones used here. Such a conclusion is in agreement with lesion studies that show that color constancy is lost after removal of V4, whereas wavelength discrimination is only mildly affected

in both man (Kennard et al. 1995; Vaina 1994) and monkey (Heywood et al. 1992; Walsh et al. 1992, 1993; Wild et al. 1985). The preservation of the capacity to discriminate between wavelengths is probably due to the integrity of areas V1 and V2, where most of the wavelength selective cells are reported to be sensitive to wavelength composition and indifferent to color (Zeki 1983). It is possible, however, that the V1 and V2 studies mentioned above did not use methods sensitive enough to detect and describe in detail more subtle modulations of cell responses as a function of perceptual changes. The effect is so straightforward in V4 that it can be detected using strict criteria or even coarse methods that are unable to detect much in other parts of the brain, which show a weaker effect and thus require a different approach. In fact, a modulation of central color responses as a function of surround illumination has been previously demonstrated not only in area V4 (Schein and Desimone 1990), but also in V1 (Wachtler et al. 2003) and even as early as the LGN (Creutzfeldt et al. 1991a,b). The main difference between these and the present study lies in the type of the modulating surround and also on the criteria used to characterize a cell as perceptually modulating. Whereas these other studies report the effects of uniform monochromatic surrounds on the responses of just one of several stimuli presented to the classical receptive field and, in the case of Wachtler et al. (2003), report weak effects without correcting for multiple comparisons, we have taken the more naturalistic approach of using large multicolor Mondrian-type surrounds to test for color-constancy and color-induction effects to the whole color-tuning function. It has been shown that color appearance depends not only on the mean color of the surround but also on the distribution of surround colors around the mean: the induction of a perceptual shift with a homogeneous background is quite different from that with a multicolored background, the latter being much closer to naturally occurring phenomenon of color constancy (Brown and MacLeod 1997). Furthermore, we did not characterize a neuron as real-color-coding when its response to a specific color alone was different under a single different background, but only when its whole color-tuning curve could be shifted in both directions across color space, in a manner equivalent to the animals' perception. To our knowledge, therefore, there are no other areas with cells reflecting color perception as strongly as the ones reported here. On the other hand, the fact that neurons modulate their chromatic responses with extra-classical receptive-field changes as early as V1 and LGN suggests that color-constancy relevant computations are initiated much earlier in the system than area V4. This has been also clearly demonstrated psychophysically, by dichoptically separating the "target" from the "surround" and showing that, in this case, there is a total failure of any spatial interactions between the two (Moutoussis and Zeki 2000). We therefore believe that, although spatial chromatic interactions begin to take place very early in the visual system, the generation of color per se is a property of higher visual areas of the brain.

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