

# Perception Matches Selectivity in the Human Anterior Color Center

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## Summary

Human ventral cortex contains at least two visual areas selective for color [1]: a posterior center in the lingual gyrus labeled V4 [2–4], V8 [5], or VO-1 [6] and an anterior center in the medial fusiform that has been labeled V4 $\alpha$  [3, 4]. We examined the properties of the anterior color center using electrical recording and electrical stimulation in a subject with an electrode implanted over the anterior color center, as determined with BOLD fMRI in the same subject. Presentation of visual stimuli evoked local field potentials from the electrode. Consistent with fMRI, the potentials were larger for chromatic than achromatic stimuli. The potentials differed depending on stimulus color, with blue-purple colors evoking the largest response. The spatial receptive field of the electrode was central/parafoveal with a contralateral bias. In the absence of a visual stimulus, electrical stimulation of the electrode produced an artificial visual percept of a blue-purple color near the center of gaze. These results provide direct evidence of a tight link between selectivity and perception in ventral temporal cortex. Electrical stimulation of the anterior color center is sufficient to produce the conscious percept of a color whose identity is determined by the selectivity of the stimulated neurons.

## Results

### Neuroimaging

Structural magnetic resonance imaging (MRI), blood-oxygenation-level dependent functional MRI (BOLD fMRI), and computed tomography were used to localize a subdural electrode implanted on the ventral temporal cortex of a human subject (Figure 1). The electrode was situated on the fusiform gyrus, mid-way between the temporal pole and the occipital pole, with standardized coordinates (26, –49, –20). The electrode was located just lateral to the collateral sulcus, in the anatomical location of the anterior color center observed in previous neuroimaging studies. BOLD fMRI showed significant color responses in the cortex proximal to the electrode (Figure 1B). Posterior to the electrode, phase-encoded retinotopic mapping revealed responses to the lower as well as the upper quadrant of the contralateral visual field, with a representation of the fovea distinct from that of V1/V2/V3, consistent with previous reports of V4 [4], V8 [5], and VO-1 [6] (Figure 1C).

### Electrical Stimulation

Pulses (300 ms) of stimulating current were passed through the electrode to evoke activity in nearby neurons, and the subject was interviewed about the resulting percept. The subject reported that stimulation of the electrode produced a percept of a “blue, purple color, like aluminum foil when it burns” and that the blue-purple percept was near the center of gaze but was not localizable to a small region of the visual field. Repeated stimulation of the electrode produced the same subjective percept. Increasing the stimulation duration to 1 s lengthened the duration of the evoked percept but did not change its quality.

To objectively confirm the patient’s report of an evoked visual percept, the subject performed a two-alternative temporal forced-choice task as the stimulation current level was randomly varied from trial to trial (Figure 2A). At low current levels, the subject could not reliably detect the electrical stimulus, resulting in chance performance (Figure 2B). At high current levels, the subject was almost always able to correctly determine the stimulation epoch, demonstrating that the stimulation produced a reliable percept. The psychometric curve showed a detection threshold of 1.7 mA (1.4–1.9 mA, 95% confidence interval). Similar current levels delivered to electrodes implanted over primary visual cortex produce the small, discrete flashes of white light known as phosphenes, thought to indicate evoked activity in a small population of pyramidal neurons surrounding the electrode [7].

### Electrical Recording

Local field potentials (LFPs) were recorded from the mid-fusiform gyrus to determine whether neurons producing the electrically evoked colored percept responded selectively to different colors. Because higher visual areas have large receptive fields, large color squares were presented that covered most of the left visual field, contralateral to the implanted electrode. Color squares evoked LFPs that began 100 ms after stimulus onset, peaked at 154 ms, and returned to baseline at 378 ms (Figure 3A). In order to calculate the amplitude of the response to each of the 26 colors, the root-mean-square (RMS) power of the LFPs was measured between 100 and 378 ms. The largest response, 102  $\mu$ V, was evoked by a blue-purple color, and the weakest response, 21  $\mu$ V, was evoked by a yellow-brown color.

The normalized cone contrast of each color square relative to the gray background was calculated using the equations  $L = (L - L_0)/L_0$ ,  $M = (M - M_0)/M_0$ , and  $S = (S - S_0)/S_0$ , where  $L$  is the long-wavelength cone response,  $M$  is the medium-wavelength cone response, and  $S$  is the short-wavelength cone response (see Table S1 available online). Two orthogonal color axes were created:  $L - M$  for long- to medium-wavelength color contrast and  $S - (L + M)$  for short-wavelength color contrast, with a third axis  $(L + M)$  for luminance [8]. Plotting response power versus color revealed that blue-purple colors evoked large responses and red-browns evoked weak responses (Figure 3B). The electrode responses were well fit ( $F = 5.7$ ,  $p = 0.005$ ) by a hyperplane with equation  $P = 7.2 \times (S - (L + M)) - 16.2 \times (L - M) + 3.6 \times (L + M) + 55.1$ , where  $P$  is response power (Figure S2 shows the iso-response plane).

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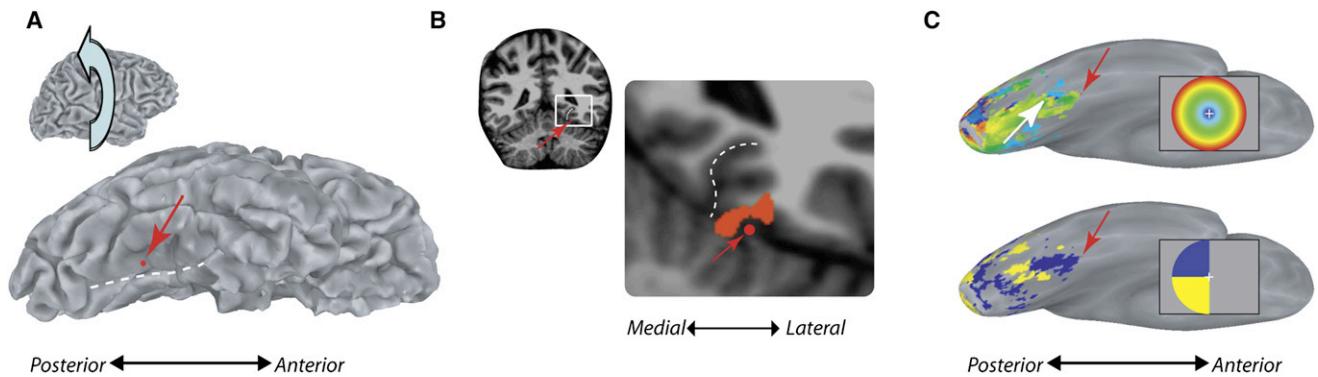


Figure 1. Location of the Implanted Electrode

(A) Lateral (top) and ventral (bottom) views of a cortical surface model of the subject's right hemisphere. The electrode, located on the fusiform gyrus, is shown as a red sphere (highlighted with a red arrow). The collateral sulcus is marked with a dashed white line.  
 (B) Coronal MR image in the plane of the electrode, shown as a red circle lateral to the collateral sulcus (dashed white line). Orange voxels showed a significant ( $p < 0.01$ ) BOLD fMRI response to color stimuli.  
 (C) Ventral view of the subject's inflated right hemisphere. The top panel shows the results of eccentricity mapping (nodes are colored according to their preferred location in the visual field, inset). Blue nodes preferred foveal stimulation. The white arrow shows the location of the ventral foveal representation; the red colored nodes and red arrow indicate the location of the electrode. The bottom panel shows the results of polar angle mapping. Blue nodes responded to visual stimulation in the upper left quadrant, yellow nodes to visual stimulation in the lower left quadrant (inset).

To quantify the difference between preferred and nonpreferred colors, the actual response powers of the five colors predicted to evoke the strongest and weakest responses by the best-fit hyperplane were compared. Preferred colors had mean response  $77 \mu\text{V}$ , and nonpreferred colors had mean response  $45 \mu\text{V}$  ( $p = 10^{-6}$ ).

Our color stimuli were not isoluminant with each other or with the background. The hyperplane fit showed a very weak positive correlation between luminance contrast and power of the electrode response (95% CI of the regression coefficient,  $-1.8$  to  $+9.0$ ). In agreement with this result, two colors that bracketed the luminance of the preferred blue-purple color ( $-1.01$  and  $-0.46$  versus  $-0.82$ ) evoked responses with dissimilar powers ( $39 \mu\text{V}$  and  $84 \mu\text{V}$  versus  $102 \mu\text{V}$ ). To directly test the relationship between luminance and response power, 8 blue stimuli and 16 achromatic squares of varying luminance were presented (Figures 3C and 3D). The blue stimuli evoked a uniformly large response ( $67 \mu\text{V} \pm 8 \mu\text{V}$  SD) with no correlation between luminance and response power ( $r = 0.12$ ,  $p = 0.8$ ). There was a weak negative correlation between luminance and response power for

achromatic squares ( $r = -0.36$ ,  $p = 0.2$ ). In sum, response power did not exhibit a consistent relationship with stimulus luminance.

The achromatic squares evoked a significantly weaker response than the blue squares ( $32 \mu\text{V}$  versus  $67 \mu\text{V}$ ,  $p = 10^{-6}$ ). Although the achromatic responses were weak, even the weakest achromatic response was significantly greater than baseline ( $p = 0.009$ ). These results are consistent with neuroimaging evidence showing that the anterior color center shows small but significant responses to achromatic stimuli [1, 9].

Previous neuroimaging studies have reported distributed responses to complex images in ventral temporal cortex. The response of the electrode to 17 chromatic images, including scenes, faces, and man-made objects that covered the same spatial extent as the uniform color squares, was measured. Many of the chromatic images that evoked large responses contained a great deal of blue, such as a picture of the Lone Ranger wearing a denim shirt against a blue sky ( $33 \mu\text{V}$ ). The mean response to all chromatic images was  $25 \mu\text{V}$ . Although it is difficult to compare responses across runs because of possible gain changes, this was weaker than the

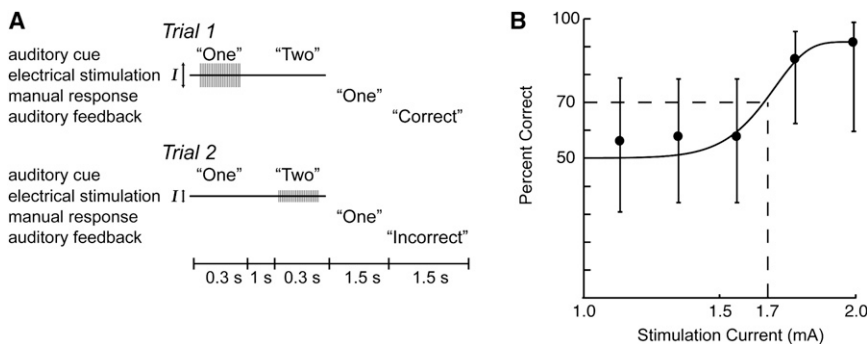


Figure 2. Stimulation of the Implanted Electrode

(A) The structure of each stimulation trial, shown for two sample trials. Each trial contained 200 Hz biphasic electrical stimulation delivered in one of two epochs. The subject attempted to detect the epoch in which the stimulation was delivered, responded with a button press after the completion of both epochs, and then received feedback. The amplitude of the stimulation current ( $I$ ) varied from trial to trial. In these examples, the first trial contained high stimulation current, and the stimulation epoch was correctly detected. The second trial contained low stimulation current, and the stimulation epoch was not correctly detected.  
 (B) Psychometric function showing percent correct detection of stimulation epoch plotted against amplitude of stimulation current ( $I$ ) for five different currents (error bars show 95% confidence intervals).

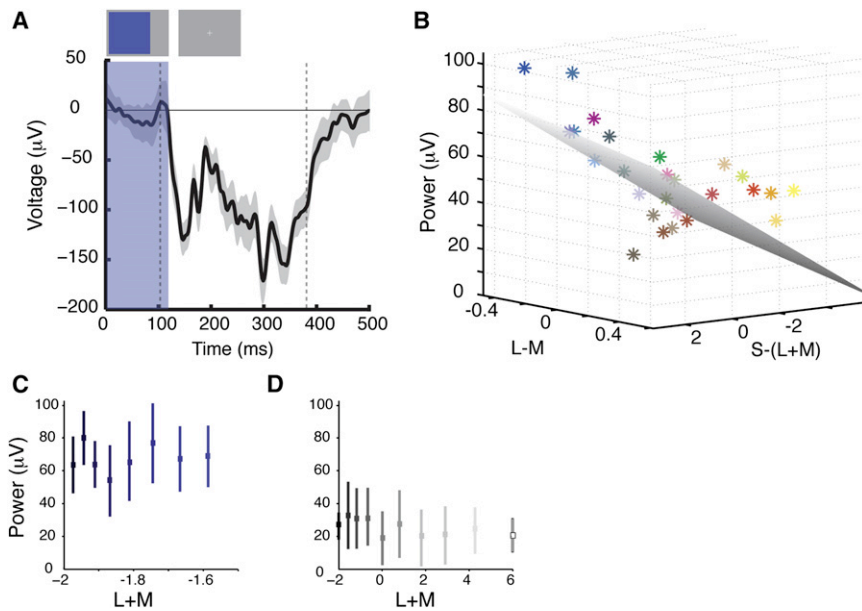


Figure 3. Response of the Implanted Electrode to Visual Stimulation

(A) Average evoked response to presentation of a blue stimulus. The stimulus is shown at the top of the plot: a blue square on a gray background was presented for 125 ms and was then replaced with a baseline display. In the plot, the heavy trace is the mean response; the gray-shaded area is the 95% confidence interval. The blue-shaded rectangle shows the stimulus duration. The dashed lines show the time interval used to calculate the response power.

(B) Power of the response to different colors. Each symbol represents the response to a color square of the same color as the symbol (stimulus configuration shown in [A]). The x axis is dimensionless  $L - M$  cone contrast, the y axis is  $S - (L + M)$  cone contrast, and the z axis is the root-mean-square response power. The best-fit plane is shown in gray.

(C) Power of the response to blue stimuli with increasing luminance contrast. Each symbol represents the average response (bars represent 95% confidence interval) to a stimulus of the same color as the symbol.

(D) Power of the response to achromatic stimuli with increasing luminance contrast. Each symbol shows the luminance of the stimulus, except for the rightmost (white) symbol, shown with a black outline for visibility.

mean response to color squares (68  $\mu\text{V}$ ). The maximum response to a chromatic image was only one-third as large as the maximum response to a color square, suggesting that simple, uniform colors are potent stimuli for this region of cortex.

Because implanted electrodes record from a small population of neurons, evoked LFPs can also be used to study spatial receptive fields. We have adapted mapping techniques similar to those used in electrophysiological studies in nonhuman primates for use in patients with implanted electrodes. These techniques allow the measurement of receptive fields in human V1 of less than a degree in size [10]. In order to measure the spatial receptive field of neurons in mid-fusiform gyrus, the preferred blue-purple stimulus was presented at different locations in the visual field, and the evoked response was measured (Figure 4). The receptive field was central/parafoveal, with a contralateral bias.

## Discussion

Human functional neuroimaging studies of color processing have focused on V1 [11, 12] or on a color-selective region in lingual gyrus in ventral occipital lobe, alternately labeled V4 [2–4], V8 [5], or VO-1 [6]. However, a number of studies have identified an additional color-selective region in mid-fusiform gyrus in ventral temporal lobe. This anterior color center, which has been labeled V4 $\alpha$  [3, 4], is active during tasks requiring color-ordering [1, 13], color imagery [14], knowledge about color [15–17], color illusions [18], and processing of object color [4, 19]. Because neuroimaging studies provide only correlational evidence about the relationship between neuronal activity and perception, it has been difficult to determine the role of the anterior color center. Electrical stimulation in the cortex of nonhuman primates allows examination of the causal relationship between activity and perception, but animals cannot report the quality of the percept evoked by stimulation [20, 21]. Electrical stimulation of human cortex can produce

a variety of visual and nonvisual percepts [22]. Stimulation of visual cortex commonly produces the percept of a single, small spot of white light known as a phosphenes [23], although colored percepts have also been reported [24–26].

Our study demonstrates a correspondence in human ventral temporal cortex between neuronal responses measured *indirectly* with BOLD fMRI and *directly* with electrical recording. Because human cortical anatomy is variable, anatomical landmarks or standard spaces cannot precisely identify the location of visual areas across subjects. Within a single subject, we demonstrate that the anterior color center, identified with BOLD fMRI, shows larger local field potentials to chromatic compared with achromatic stimuli.

A striking concordance was observed between the percept evoked by electrical stimulation and the selectivity for visual

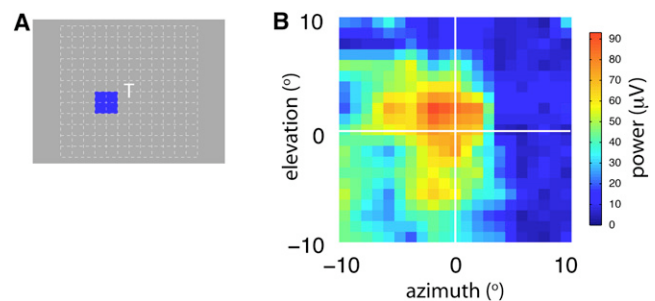


Figure 4. Receptive Field of the Implanted Electrode

(A) The visual stimulus used for receptive field mapping. Blue squares were presented in 121 visual field locations (white dashed lines, not present on actual display, show all possible locations). The subject performed a detection task on foveally presented letters to ensure fixation.

(B) The power of the evoked electrical response from the electrode for stimuli presented at each visual field location, interpolated to account for overlap between adjacent stimuli. Color indicates strength of the response. White crosshairs show the horizontal and vertical meridians for reference.

stimuli of neurons in mid-temporal lobe. In addition to evoking action potentials from nearby neurons, electrical stimulation can activate fibers of passage [7]. Because the local field potential from neurons near the electrode was color selective and matched the evoked percept, the color percept in our study could not have arisen from stimulation of unrelated fibers of passage. The minimum current level required to evoke a percept was several-fold lower than current levels reported in previous studies [25, 26], further suggesting that the subject's percept of "blue" was produced by activity in a small population of neurons surrounding the electrode. Studies in nonhuman primates have suggested that patchy domains in V1 [27] and V2 [28] are selective for individual colors; a recent report suggests that the same may be true in human visual cortex (I. Kuriki et al., 2007, Soc. Neurosci., abstract). In our study, electrical stimulation evoked only one chromatic sensation. This could be the result of an organization by color in the human anterior color center. Stimulation of a group of neurons near the electrode, all selective for a similar color, could create the percept of that color. Evidence for this idea comes from the observed color-selective local field potentials. If neighboring neurons were selective for completely different colors, the local field potential (the result of synaptic activity near the electrode) would not be expected to be strongly color selective.

Unlike earlier stages of color processing, in mid-fusiform gyrus the color selectivity extends over a large portion of visual space. Correspondingly, stimulation of this area resulted in a diffuse chromatic percept, unlike the small, discrete phosphenes produced by electrical stimulation of V1.

Neuroimaging studies in humans and monkeys have identified color responses in V1, V2, VP, V4/V8/VO-1, and the anterior color center [29–32]. While patients with lesions to occipitotemporal cortex can present with a variety of color vision disturbances [13, 33–37], it has been difficult to determine the relationship between activity in different identified visual areas and color perception. We demonstrate a close correspondence in one of these areas—the human anterior color center—between visually evoked activity, electrical stimulation, and the conscious percept of color.

#### Experimental Procedures

The subject was a 38-year-old right-handed male with a 5 year history of medically intractable complex partial seizures of unknown etiology. An array of subdural electrodes was implanted to determine the location of the seizure focus, guided solely by clinical criteria, and included a six-contact strip electrode implanted laterally-to-medially on the right ventral temporal cortex. One week before electrode implantation, BOLD fMRI was used to localize visual areas. MRI data were analyzed using AFNI [38]. Cortical surface models were constructed with FreeSurfer [39] and visualized in SUMA [40]. Following implantation, a whole-head computed tomography scan was obtained and aligned to the presurgical structural MRI. Analysis of clinical EEG recordings by the clinical neurophysiology team determined that the seizures did not originate from the region of cortex covered by the ventral temporal strip of electrodes. Electrical stimulation and recording for research purposes was performed on these electrodes. Informed consent was obtained from the subject, and all procedures were approved by the Baylor College of Medicine Institutional Review Board or the Committee for the Protection of Human Subjects at the University of Texas Health Science Center at Houston. For a complete description of the [Experimental Procedures](#), please see the [Supplemental Data](#).

#### Supplemental Data

The Supplemental Data for this article can be found online at <http://www.current-biology.com/cgi/content/full/18/3/216/DC1>.

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## Colour Vision: Cortical Circuitry for Appearance

Directly stimulating certain cortical neurons can produce a color sensation; a case is reported in which the color perceived by stimulation is the same as the color that most effectively excites the cortical circuitry.

Brian Wandell

One of the great achievements of neuroscience is the complete description of the early stages of color vision. In the human retina there are three types of cone containing different light absorbing pigments, each with its own unique sensitivity to the wavelengths of light. Because we acquire only three cone-type samples, and thus critically under-sample the available wavelength information, we are quite poor at resolving the wavelength information in a scene. The design of nearly every modern imaging technology — from displays to printers to cameras — takes advantage of the fact that humans encode light using only three types of cone. Technology standards show us how to capture and display enough information to persuade the cones that they are looking at the original scene [1].

Cones are clearly central to color vision, but the relationship between cone responses and our color perception is not straightforward. Retinal and cortical circuits process the cone responses to create our experience of color. These processes can be revealed by visual demonstrations in which the same cone photon absorptions produce different lightness and color appearance (Figure 1). Some principles of the neural coding — most importantly, the fact that the cone signals are recombined in the retina into three channels, known as opponent-colors, which are made up of sums and differences of local cone responses — are also used in engineering standards, including television transmission and image compression.

But, we do not have theories that accurately predict the patterns of color we perceive. How cortical circuitry interprets the encoded information remains a grand challenge for color science. For many years, the location of the essential cortical circuitry of color was a very contentious point, with many investigators doubting the very existence of any cortical specializations for color. Neuroimaging and neurological case studies over the last century demonstrate that signals in ventral occipital cortex (Figure 2) are

essential for the perception of color [2]. For example, responses in a portion of ventral occipital cortex rise and fall as subjects alternately view colored and luminance-matched achromatic objects [3]. Damage to these same regions of cortex produces a syndrome known as cerebral achromatopsia — a color disturbance of cortical origin. Rather remarkably, in this syndrome color perception is severely altered without any obvious interference with other abilities, such as form, motion or depth perception [4,5].

In a paper published recently in *Current Biology*, Murphey *et al.* [6] provide a glimpse into the relationship between brain activity, brain stimulation and color perception. Their work bypasses the intricate color machinery of the retina and cortex. Instead, they study a patient who had an electrode array implanted in order

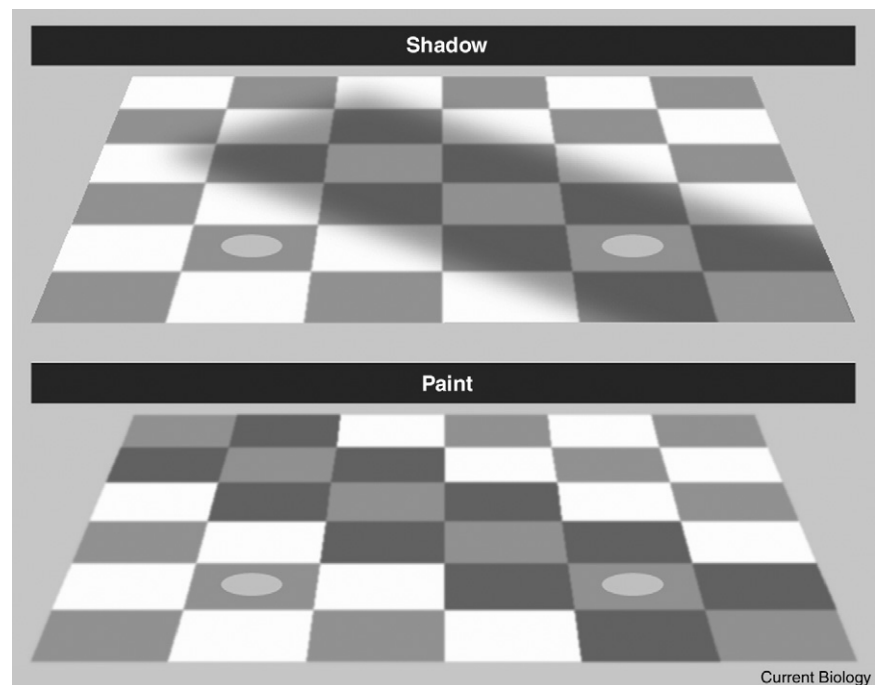


Figure 1. Two images which are identical apart from the shadow penumbra. In the second image, the penumbra is replaced by a sharp edge coinciding with the checkers. Most people see a greater difference in the lightness of the spots in the shadow (top) than in the paint (below). The appearance difference is not caused by differences in cone signals, but rather by the neural circuitry's analysis of the absorptions. (Reprinted from [16].)

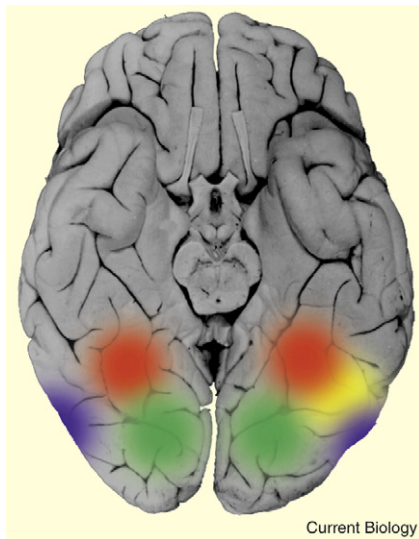


Figure 2. Specific regions in the human ventral cortex appear to contain circuitry essential for various behaviors.

The location of a region essential for color is indicated in green. Regions containing circuitry essential for faces, motion and reading are indicated by red, blue and yellow. (Reprinted from [17].)

to localize regions of healthy and diseased cortex. The electrodes turned out to be in a healthy location of cortex, near one of the regions that has been identified as particularly responsive to color. The location is a few centimeters anterior to the location identified in neurological cases of cerebral achromatopsia. The authors show that they can measure a significant response to colored stimuli by one of the electrodes; that some of the color stimuli are more effective than others; and that stimulating cortex with this electrode evokes a visual sensation corresponding to the most effective color stimulus. Making such measurements in the human brain is particularly valuable because the subject can offer a verbal description of the experience caused by the stimulation. The stimulation data add support to the wealth of neuroimaging data suggesting a critical role for these regions in color perception.

In the face of a neuroscience literature documenting the intricacies of the molecular and neural circuitry of circuit function, results like this are amazing and puzzling. Somehow, current pulses from a 2.2 mm diameter electrode near the cortical surface generate just the right circuit response to evoke a recognizable color percept. This study is not alone in reporting the

effectiveness of such stimulation at evoking a recognizable percept. A classic investigation of stimulation in primary visual cortex (V1) showed a correspondence between the receptive field location and the perceived position of the evoked perceptual activity [7]. These have been followed by a few other studies, including some that showed that low stimulation levels in V1 can produce phosphenes [8]; these are generally small spots or oriented lines but they can appear in a variety of colors. A more recent study [9] summarizing stimulation from many regions within visual cortex showed that stimulation produces visual percepts of varying complexity. In that study, measurements were made in nearly 1200 electrodes from 23 patients.

About one-fifth of the surface electrodes generated a visual perception, and it is likely that if one counted the ability to modify a percept the percentage would have been even higher. The visual percepts caused by the stimulation were well correlated with the conclusions of neurological and neuroimaging studies. Depending on the electrode placement, subjects perceived a range of forms from dots, to geometric shapes (triangles, diamonds), to hallucinations of animals, people or landscapes.

These results teach us that even the simplest stimulation is capable of stirring up a perceptually meaningful response from the cortical circuitry. One possibility is that the complex molecular and neural circuitry that serves this portion of the brain is tolerant of a wide range of potential inputs, and that nearly any stimulation of this circuitry evokes a characteristic (resonant) response. The resonant response of these specific circuits is the experience of color.

Historically, there have been few electrical stimulation measurements in the human brain. This is likely to change during the next decade. The success of deep brain stimulators in alleviating the symptoms of Parkinson's Disease [10], the hope that such methods will be useful in other disorders [11–13], and significant advances in the means to control neural signaling will increase the number and type of stimulation experiments [14,15]. For these applications to succeed, we must obtain a deeper understanding of the consequences of stimulation for various types of perception, ranging

from color and sight to emotions. The work of Murphey *et al.* [6], combining perceptual measurements, electrical measurements and electrical stimulation, is a useful contribution towards that understanding.

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