15. Sohrmann, M., Fankhauser, C., Brodbeck, C., and Simanis, V. (1996). The dmf1/mid1 gene is essential for correct positioning of the division septum in fission yeast. Genes Dev. *10*, 2707–2719.
16. Chang, F., Woollard, A., and Nurse, P. (1996). Isolation and characterization of fission yeast mutants defective in the assembly and placement of the contractile actin ring. J. Cell Sci. *109*, 131–142.
17. Kozlov, M.M., and Bershadsky, A.D. (2004). Processive capping by formin suggests a force-driven mechanism of actin polymerization. J. Cell Biol. *167*, 1011–1017.

Temasek Life Sciences Laboratory,
1 Research Link, 117604 Singapore.
*E-mail: snejana@tll.org.sg

DOI: 10.1016/j.cub.2008.01.029

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

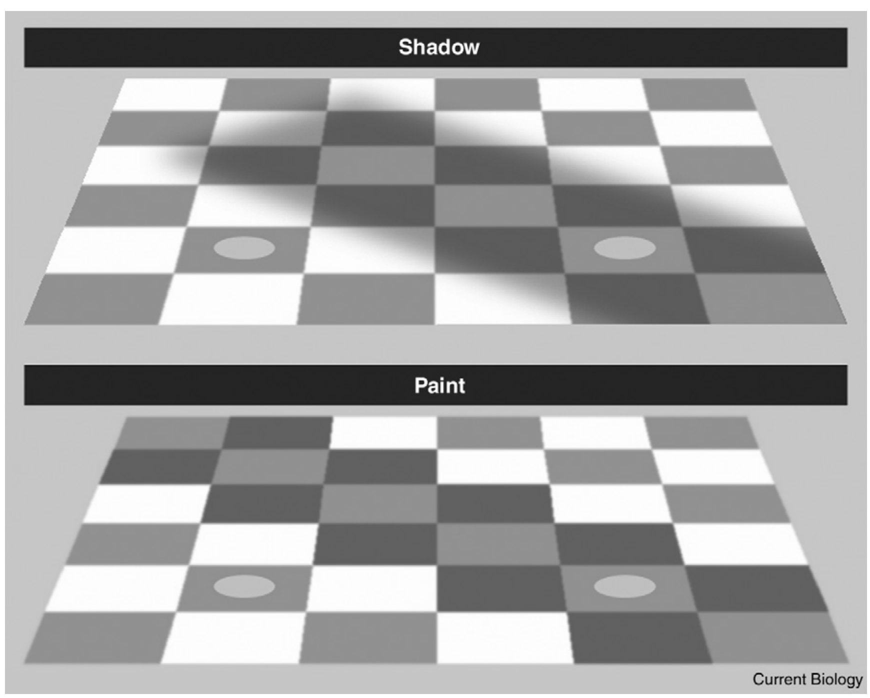

Figure 1. Two images which are identical apart from the shadow penumbra.
In the second image, the penumbra is replaced by a sharp edge coinciding with the checkers. Most people see a greater difference in the lightness of the spots in the shadow (top) than in the paint (below). The appearance difference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

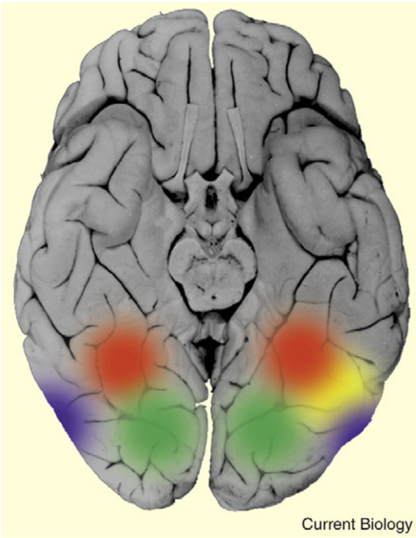

Figure 2. Specific regions in the human ventral cortex appear to contain circuitry essential for various behaviors.

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.

References

1. Wandell, B.A. (1995). Foundations of Vision (Sunderland, MA: Sinauer Press).
2. Zeki, S. (1993). A Vision of the Brain (London: Blackwell Scientific Publications).
3. Zeki, S., Watson, J.D., Lueck, C.J., Friston, K.J., Kennard, C., and Frackowiak, R.S. (1991). A direct demonstration of functional specialization in human visual cortex. J. Neurosci. *11*, 641–649.
4. Meadows, J. (1974). Disturbed perception of colours associated with localized cerebral lesions. Brain *97*, 615–632.
5. Bouvier, S.E., and Engel, S.A. (2006). Behavioral deficits and cortical damage loci in cerebral achromatopsia. Cereb. Cortex *16*, 183–191.
6. Murphey, D.K., Yoshor, D.I., and Beauchamp, M.S. (2008). Perception matches selectivity in the human anterior color center. Curr. Biol. *18*, 216–220.
7. Brindley, G.S., and Lewin, W.S. (1968). The sensations produced by electrical stimulation of the visual cortex. J. Physiol. *196*, 479–493.
8. Bak, M., Girvin, J.P., Hambrecht, F.T., Kufta, C.V., Loeb, G.E., and Schmidt, E.M. (1990). Visual sensations produced by intracortical microstimulation of the human occipital cortex. Med. Biol. Eng. Comput. *28*, 257–259.
9. Lee, H.W., Hong, S.B., Seo, D.W., Tae, W.S., and Hong, S.C. (2000). Mapping of functional organization in human visual cortex: electrical cortical stimulation. Neurology *54*, 849–854.
10. Benabid, A.L. (2003). Deep brain stimulation for Parkinson's disease. Curr. Opin. Neurobiol. *13*, 696–706.
11. Houeto, J.L., Karachi, C., Mallet, L., Pillon, B., Yelnik, J., Mesnage, V., Welter, M.L., Navarro, S., Pelissolo, A., Damier, P., *et al*. (2005). Tourette's syndrome and deep brain stimulation. J. Neurol. Neurosurg. Psych. *76*, 992–995.
12. Mallet, L., Mesnage, V., Houeto, J.L., Pelissolo, A., Yelnik, J., Behar, C., Gargiulo, M., Welter, M.L., Bonnet, A.M., Pillon, B., *et al*. (2002). Compulsions, Parkinson's disease, and stimulation. Lancet *360*, 1302–1304.
13. Mayberg, H.S., Lozano, A.M., Voon, V., McNeely, H.E., Seminowicz, D., Hamani, C., Schwalb, J.M., and Kennedy, S.H. (2005). Deep brain stimulation for treatment-resistant depression. Neuron *45*, 651–660.
14. Zhang, F., Aravanis, A.M., Adamantidis, A., de Lecea, L., and Deisseroth, K. (2007). Circuit-breakers: optical technologies for probing neural signals and systems. Nat. Rev. Neurosci. *8*, 577–581.
15. Zhang, F., Wang, L.P., Boyden, E.S., and Deisseroth, K. (2006). Channelrhodopsin-2 and optical control of excitable cells. Nat. Methods *3*, 785–792.
16. Hillis, J.M., and Brainard, D.H. (2007). Distinct mechanisms mediate visual detection and identification. Curr. Biol. *17*, 1714–1719.
17. Wandell, B.A., Dumoulin, S.O., and Brewer, A.A. (2008). Visual cortex in humans. In New Encyclopedia of Neuroscience, L. Squire, T. Albright, F. Bloom, F. Gage, and N. Spitzer, *et al*., eds. (Elsevier), in press.

Department of Psychology, Building 420
Room 484, Stanford University, California
94305-2130, USA.
E-mail: wandell@stanford.edu

DOI: 10.1016/j.cub.2008.01.045