Current Biology 17, 862–867, May 15, 2007 ©2007 Elsevier Ltd All rights reserved DOI 10.1016/j.cub.2007.03.066

Report

Behavioral Detection of Electrical Microstimulation in Different Cortical Visual Areas

Dona K. Murphey[2] and John H.R. Maunsell[1,2,*]
[1] Howard Hughes Medical Institute and
[2] Department of Neuroscience
Baylor College of Medicine
One Baylor Plaza
Houston, Texas 77030

Summary

The extent to which areas in the visual cerebral cortex differ in their ability to support perceptions has been the subject of considerable speculation. Experiments examining the activity of individual neurons have suggested that activity in later stages of the visual cortex is more closely linked to perception than that in earlier stages [1–9]. In contrast, results from functional imaging, transcranial magnetic stimulation, and lesion studies have been interpreted as showing that earlier stages are more closely coupled to perception [10–15]. We examined whether neuronal activity in early and later stages differs in its ability to support detectable signals by measuring behavioral thresholds for detecting electrical microstimulation in different cortical areas in two monkeys. By training the animals to perform a two-alternative temporal forced-choice task, we obtained criterion-free thresholds from five visual areas—V1, V2, V3A, MT, and the inferotemporal cortex. Every site tested yielded a reliable threshold. Thresholds varied little within and between visual areas, rising gradually from early to later stages. We similarly found no systematic differences in the slopes of the psychometric detection functions from different areas. These results suggest that neuronal signals of similar magnitude evoked in any part of visual cortex can generate percepts.

Introduction

Although it has long been known that the visual cerebral cortex is subdivided into many distinct hierarchically organized areas, it remains unclear whether certain regions of the visual cortex are more tightly coupled to perception. The demonstration that neurons in later stages of visual cortex have more complicated response properties than those in early stages led to the suggestion that perceptions may depend on the activity of relatively few neurons in the higher visual cortex [16, 17]. Recent measurements of the activity of individual neurons support the idea that later stages are more tightly associated with perception. For example, correlations between the responses of single cells and perceptual reports are stronger in later stages of cortex during binocular rivalry (see [1]), during detection or discrimination of direction [2–5] or binocular disparity [6], and during viewing of anticorrelated random-dot stereograms [7, 8]. Imaging studies in humans have similarly found that the changes in signals related to rivalry are weaker in V1 than in later stages of the visual cortex (see [1, 9]).

On the other hand, results from functional imaging, transcranial magnetic stimulation, and lesion studies have been used to argue either that perception can depend specifically on neurons in the earliest levels of the visual cortex [10–15] or that neurons in all parts of the visual cortex can contribute equally to perception [18, 19]. In still another formulation, it has been suggested that neuronal activity in the ventral stream of processing is more important for visual experience than activity in the dorsal stream [20].

To directly explore whether some cortical areas can more readily generate percepts than others, we have measured behavioral thresholds for detecting electrical microstimulation in a range of areas spanning all levels of the visual cortex. It has long been known that electrical microstimulation of a site in or near V1, the first stage of the visual cortex, can produce a specific, repeatable visual percept, called a phosphene ([21–23], see [24]). Electrical stimulation of later stages of the visual cortex can produce more elaborate visual or multimodal experiences [25]. If neuronal signals in some cortical areas are more tightly linked to perception, smaller changes in activity in those areas, relative to others, may suffice to create detectable percepts. Thus, thresholds for detecting electrical microstimulation are expected to be lower in those areas.

Microstimulation thresholds have been measured in monkey V1 [26, 27] and at a few sites in extrastriate visual cortex [28]. However, threshold measurements in previous experiments may have been substantially influenced by the criteria subjects used for determining whether they would report that they perceived something [29]. Internal response criteria could vary greatly for percepts arising from stimulation at different sites, depending on whether they appear more or less natural. This would increase the variance of thresholds within an area and produce systematic offsets between thresholds for different areas. We describe here the first measurements of cortical-microstimulation thresholds by using methods that essentially eliminate the effects of the subject's criterion and thus allow measurements from different brain regions to be compared directly.

Results

Two rhesus monkeys (*Macaca mulatta*) were trained to do a two-alternative temporal forced-choice task (Figure 1). During each trial, the animal fixated on a small white spot centered on an unstructured gray background. While the animal fixated, two sequential 250 ms intervals were presented, each marked by a tone. A stimulus was delivered during one of the intervals, which was randomly selected for each trial. Shortly after the end of the second interval, two targets appeared,

*Correspondence: maunsell@hms.harvard.edu

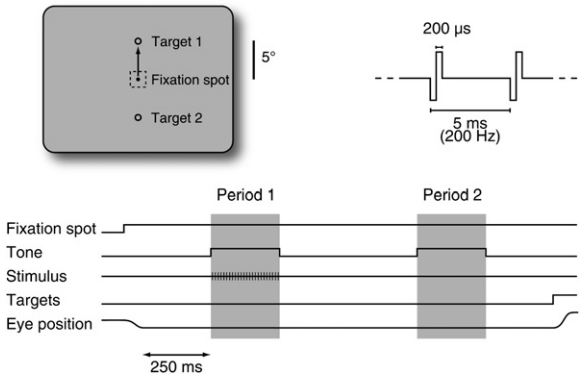

Figure 1. Two-Alternative Forced-Choice Task

During fixation, a stimulus was delivered during one of two 250 ms time intervals that were marked by auditory tones and separated by 500 ms. Two-hundred and fifty milliseconds after the end of the second interval, two response targets appeared, and the animals indicated which interval contained the stimulus by making a direct saccade to the appropriate target (target 1 for period 1). The electrical stimuli were 250 ms trains of constant current pulses at 200 Hz, with the current randomly selected on each trial.

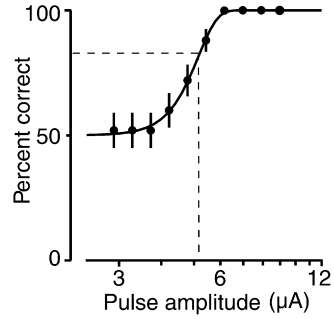

Figure 2. Representative Psychometric Function

Behavioral performance at a V1 site. Fifty repetitions of each of ten currents were delivered in random order. The points show the average performance (±1 SE), and the curve is the best-fitting psychometric function (see Experimental Procedures). Threshold at each site was taken as the current corresponding to 82% correct performance on this curve (dashed lines).

5° above and below the fixation spot. The animal indicated which interval contained the stimulus by making a saccade directly to the appropriate target—up for interval one; down for interval two. Thus, the animals reported only the detection of the stimulus, not the apparent location or other properties of the percept.

Each animal was initially trained with small, peripheral, low-contrast visual stimuli. During data collection, cortical microstimulation with a metal microelectrode replaced the visual stimulus. Behavioral-detection thresholds were measured in V1, V2, and the anterior inferotemporal cortex (IT) in both animals. Additionally, we measured thresholds in V3A and the middle temporal area (MT) in the second animal. For each visual area examined, both monkeys required a period of up to a few days of training during which microstimulation-detection thresholds fell and stabilized. After thresholds had stabilized for an area, we attempted to sample uniformly from all layers of the cortex, with successive stimulation sites typically separated by 250 μm (and by no less than 190 μm).

The animals detected microstimulation with low currents at every site tested in visual cortex, with each site yielding a well-formed psychometric function (Figure 2). Threshold for each site was taken as the current that yielded 82% correct detection (see Experimental Procedures).

Threshold distributions for the different areas are plotted in Figure 3. Although we sampled from all layers, there was little variance in the distribution for each area. The average coefficient of variation for the threshold distributions in Figure 3 was 0.18. Moreover, thresholds were highly consistent for the two subjects. The median thresholds for V1 for the two animals were 5.2 and 6.6 μA (interquartile ranges: 4.4–6.4 and 5.2–8.6 μA). Current pulses in this range (<10 μA) should directly excite neurons over no greater than a 100 μm radius [27, 30], a small fraction of the thickness of the macaque cortex. Although the anatomy of V2 is quite distinct from V1, thresholds in V2 differed only slightly (1.2× and 1.3× greater those in V1 for the two animals). Thresholds for IT were somewhat higher (2.0× and 1.7× those in V1 for the two animals). In the second animal,

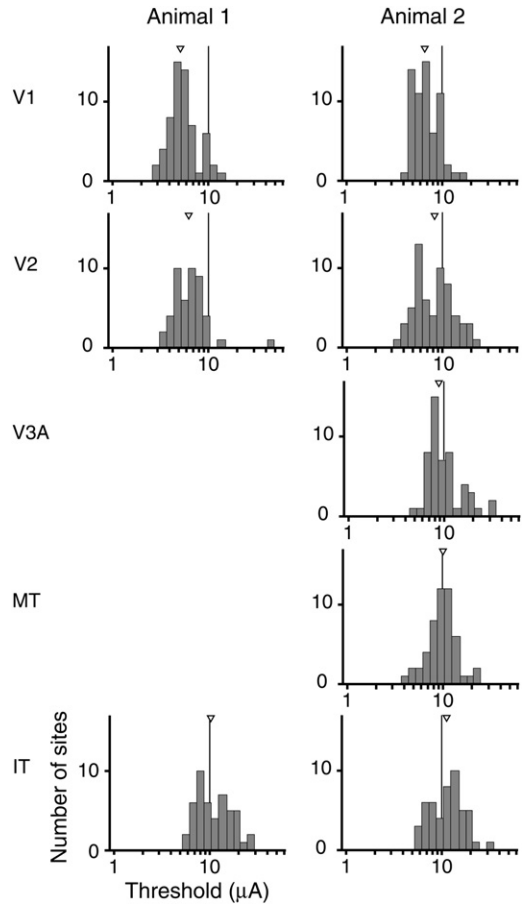

Figure 3. Distributions of Detection Thresholds

Median thresholds are marked by a triangle. Medians and interquartile ranges for the two animals were as follows: V1, 5.2 μA (4.4–6.4 μA), 6.6 μA (5.2–8.6 μA); V2, 6.3 μA (4.9–7.6 μA), 8.3 μA (5.8–11.5 μA); V3A, 8.9 μA (7.7–12.2 μA); MT, 10.1 μA (8.1–11.9 μA); and IT, 10.3 μA (8.2–15.5 μA), 11.3 μA (7.5–15.2 μA).

we also measured thresholds in areas V3A and MT, which lie in the dorsal pathway. Thresholds in those areas were intermediate, consistent with their position in the hierarchy of cortical areas [31]. Overall, detection thresholds throughout the visual cortex increased progressively from V1 to later stages. The differences between thresholds across areas were highly significant for both animals ($p < 10^{-13}$ and $p < 10^{-10}$; Kruskal-Wallis test). Nevertheless, the changes were moderate, with substantial overlap in the distributions for all areas and both animals reliably detecting 25 μA currents at virtually every site tested.

The psychometric-detection function is characterized by a slope in addition to a threshold. Shallower slopes are associated with less sensitivity or greater noise and might be expected for stimulation sites that are further from a site of detection. Figure 4 illustrates the distribution of slopes for sites with dependable slope estimates (see Experimental Procedures). Only for animal 2 was there a significant difference in slope across cortical areas ($p < 10^{-4}$; Kruskal-Wallis test), and neither animal had a significant correlation between slope and rank in the cortical hierarchy ($p > 0.32$). Overall, the slopes of the psychometric functions did not suggest that particular cortical visual areas exercise special privilege in supporting percepts.

We tested for statistically significant correlations between threshold or slope and (1) depth in penetration (laminar differences), (2) time in data-collection course for a given area (perceptual learning), and (3) time in day (learning or adaptation within a day). We also examined the relationship between threshold and slope, which are correlated when steeper slopes are achieved by suppressing responses to weak signals ("squelching," see [32]). These seven tests were based on a correlation coefficient generated from a least-squares fit of the data ($p < 0.05$ with Bonferroni correction). Across all the areas in both subjects, this amounted to 56 tests, of which a few reached statistical significance. However, the significant correlations followed no obvious pattern; threshold versus time in data-collection course for V1 in animal 1, $r = -0.60$ ($p < 10^{-7}$) and threshold versus depth in penetration for IT in animal 1, $r = -0.53$ ($p < 0.0001$); threshold versus time in day for V3A in animal 2, $r = -0.48$ ($p < 0.0003$); and threshold versus depth in penetration for V3A in animal 2, $r = -0.46$ ($p < 0.0007$). Both subjects had slightly higher thresholds in the superficial layers of V1 (sites <1.0 mm below the cortical surface), but the difference was small and significant only for one animal (animal 1 was 27% higher, $p = 0.18$; animal 2 was 18% higher, $p = 0.0001$). For those areas in which the center of the multiunit receptive field was precisely mapped (V1, V2, and V3A), there was no correlation between receptive-field eccentricity and the threshold or slope of the detection function.

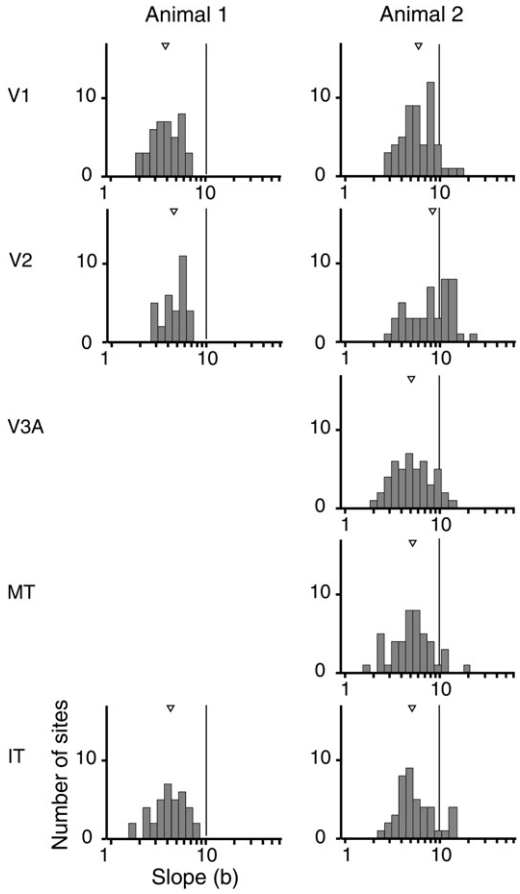

Figure 4. Distributions of Psychometric Slopes

Summary slope histograms for all sites with reliable slope estimates (see Experimental Procedures). Medians and interquartile ranges for the two animals were as follows: V1, 4.5 (3.0–5.2), 6.0 (4.4–8.1); V2, 5.6 (4.9–7.6), 8.4 (5.2–11.5); V3A, 5.0 (3.6–6.6); MT, 5.2 (3.7–6.5); and IT, 4.8 (3.3–5.7), 5.2 (4.0–7.0).

Discussion

We have found that thresholds for detecting electrical microstimulation are similar across the visual cerebral cortex and rise slowly and progressively in successive stages. There are several reasons these results must be interpreted with caution, however. First, although microstimulation makes it possible to measure the effects of changing the activity of neuronal elements in a single, identified cortical area, it does not create patterns of activity like those during normal vision. Although we modulated cortical activity arising from normal visual stimulation (viewing a fixation spot on an otherwise blank display), it remains possible that thresholds might have been different if it were possible to artificially activate spatial patterns of activity more closely resembling those created by visual stimuli. Second, it is possible that a close link between neuronal activity and perception in later stages was counterbalanced by unidentified factors that raised thresholds for detecting microstimulation in those areas. Finally, although thresholds were lower in earlier visual areas, it is possible that those thresholds were mediated by indirect, convergent activation of neurons in the highest levels of the visual cortex. Conversely, it is possible that thresholds in later stages were mediated by indirect activation of neurons in V1 (this would explain why thresholds rose in later stages). However, obligatory activation of either the earliest or latest areas seems unlikely given the overlap in threshold and slope distributions found at opposite extremes of the visual cortex. Additionally, a recent study involving combined electrical microstimulation with

functional imaging found that most electrically evoked activity in neocortex was limited to areas monosynaptically connected with the stimulation site (Logothetis et al., abstract No. 114.10 presented at the 2006 Society for Neuroscience meeting in Atlanta, GA).

Although uncertainties remain about how microstimulation leads to perception, the overlapping threshold distributions for behavioral responses to microstimulation across different visual areas suggest that activation of a comparable number of neurons in any visual area suffices for generating a behaviorally detectable signal. They do not support the idea that later stages are more closely linked to perception or that earlier stages have a distinctly privileged role. Similarly, the results from V3A and MT suggest that areas in the dorsal pathway are not inferior to areas in the ventral pathway in their ability to support percepts. Our results are more consistent with the idea that neuronal signals anywhere in the visual cortex have comparable capacity for contributing to perceptual decisions and that performance on a particular visual task is based most directly on those neurons that provide the most reliable signals for that task, regardless of their position in the cortical visual hierarchy [19, 33].

The origin of the systematic changes in thresholds from V1 to IT remains unclear. Because we always tested in a sequence from V1 to IT, better performance in earlier stages cannot be because of the animals' learning how to generalize to new percepts. Several anatomical differences mirror the progressive increases we found, including the spread of intrinsic connections [34, 35], the size of pyramidal cell bodies, and the extent and complexity of their dendritic fields [36]. On the other hand, the fact that the radically different architecture and thalamocortical inputs of V1 are not associated with markedly different thresholds suggests that thresholds are not greatly affected by details of cortical architectonics.

Further experiments will be needed to explain the disparity between the current results and previous studies that suggested that later stages in visual cortex are more closely linked to perception. One possibility is that previous studies involved visual functions that are specifically mediated by those regions of the cortex. For example, studies of rivalry may have found closer correlations between neuronal activity and perceptual reports in the later visual cortex because later stages play a special role in rivalry. Because lesions restricted to higher stages in the cortical hierarchy do not affect performance on simple discrimination tasks [37, 38], it is possible that tasks involving simple visual attributes or those involving precise spatial localization, such as hyperacuity, might reveal stronger correlations between behavior and neuronal activity in intermediate or early areas.

The detection thresholds we found in V1 are comparable to those found in an earlier study of detection of microstimulation in monkey V1 [26] and are comparable with thresholds for microstimulation with chronically implanted microelectrodes near V1 in a human subject [39]. We found less variance in the thresholds of different stimulation sites, probably owing to the use of a forced-choice design. Other studies in monkeys [30] and humans [40] have described higher thresholds for generating a behavioral response in the superficial layers of V1, as we describe here. In contrast, DeYoe and his colleagues [26] reported that the lowest detection thresholds in monkey V1 are found in the superficial layers. This discrepancy may arise from differences in behavioral tasks or stimulation protocols.

The current results are relevant to experiments that explore how microstimulation affects the perception of visual stimuli (e.g., [41–43]). These studies seek to perturb perception without the animal knowing when the electrical stimulus was delivered, but currents used are often higher than those that were reliably detectable here. In our task, microstimulation was detected while the monkeys viewed a blank display, and it is possible that higher currents would be needed to detect microstimulation in conjunction with visual stimuli (but see [22]). Nevertheless, these other microstimulation studies must be carefully interpreted because they could have been influenced by an induced percept, either visual or otherwise [44]. Our results raise questions about interpretations that specifically argue against the detection of microstimulation during particular tasks [45].

Finally, we note that much of the work on developing neural prostheses has focused on stimulation of primary sensory and motor areas. The relatively uniform detection thresholds found in the visual cortex and similarly low detection thresholds described in the somatosensory and prefrontal cortex [46] raise the possibility that most regions of the neocortex might be exploited for evoking percepts.

Experimental Procedures

All experiments conformed to protocols approved by the Baylor College of Medicine Institutional Animal Care and Use Committee.

Electrical Stimulation

The electrical stimulus was a train of constant current 200 μs biphasic pulses delivered at 200 Hz for 250 ms through a Pt/Ir electrode (~0.2–1.5 MΩ at 1 kHz). At each cortical stimulation site, 50 repetitions of six to ten current levels spanning behavioral threshold were tested in a randomly interleaved order. All currents are given as the pulse amplitude (not peak-to-peak). In both animals, we collected data first from V1 and then sampled areas in hierarchical order [31], ending with IT. We typically stimulated at many regularly spaced sites along one electrode penetration each day. In animal 1, we found that thresholds began to rise over the course of 13 penetrations in a small region of V1. We excluded those data from analysis and limited sampling density for the data reported here.

Identifying Visual Areas

V1, V2, MT, and IT were targeted with sulcal landmarks in structural MR images and stereotaxic locations [47]. Their locations were confirmed with response properties and receptive-field locations and sizes. Recordings were made from the general area of V3A on the anterior bank of the lunate sulcus, but because it lacks response properties or a topographic organization that can distinguish it from V3 [48], it is possible that some putative V3A sites may have been in V3. Because most penetrations were in a region that included receptive fields in the superior contralateral quadrant, we strongly suspect that all the sites were in V3A.

Psychometric Functions

Neither animal had an obvious response bias. During data collection, interval 1 was selected 52% of the time by animal 1 and 47% of the time by animal 2. Behavioral responses on the two-alternative forced-choice detection task were fit to the cumulative Weibull function [49]:

$$p = 1 - \gamma - (\gamma + 0.5)e^{-(c/\alpha)^{\beta}}$$

The parameter α is the current yielding to 82% correct responses and was taken as the threshold. The parameter β determines the steepness (slope) of the function. Sites were excluded from the analysis of slopes if fewer than two sampled currents fell between 55 and 95% correct on the best fitting function, because those cases tended to have artificially high slopes.

Acknowledgments

We thank William Bosking, Joonyeol Lee, Xinmiao Peng, and Daniel Yoshor for their insights and suggestions during all stages of this project. We also thank Michael Beauchamp for comments on the manuscript and Vivian Imamura, Dennis Murray, and Tori Williford for technical assistance. This work was supported by National Institutes of Health R01EY05911. J.H.R.M. is an Investigator with the Howard Hughes Medical Institute.

Received: January 18, 2007
Revised: March 3, 2007
Accepted: March 29, 2007
Published online: April 26, 2007

References

1. Blake, R., and Logothetis, N.K. (2002). Visual competition. Nat. Rev. Neurosci. *3*, 13–21.
2. Williams, Z.M., Elfar, J.C., Eskandar, E.N., Toth, L.J., and Assad, J.A. (2003). Parietal activity and the perceived direction of ambiguous apparent motion. Nat. Neurosci. *6*, 616–623.
3. Cook, E.P., and Maunsell, J.H.R. (2002). Attentional modulation of behavioral performance and neuronal responses in middle temporal and ventral intraparietal areas of macaque monkey. J. Neurosci. *22*, 1994–2004.
4. Celebrini, S., and Newsome, W.T. (1994). Neuronal and psychophysical sensitivity to motion signals in extrastriate area MST of the macaque monkey. J. Neurosci. *14*, 4109–4124.
5. Britten, K.H., Newsome, W.T., Shadlen, M.N., Celebrini, S., and Movshon, J.A. (1996). A relationship between behavioral choice and the visual responses of neurons in macaque MT. Vis. Neurosci. *13*, 87–100.
6. Nienborg, H., and Cumming, B.G. (2006). Macaque V2 neurons, but not V1 neurons, show choice-related activity. J. Neurosci. *26*, 9567–9578.
7. Janssen, P., Vogels, R., Liu, Y., and Orban, G.A. (2003). At least at the level of inferior temporal cortex, the stereo correspondence problem is solved. Neuron *37*, 693–701.
8. Cumming, B.G., and Parker, A.J. (1997). Responses of primary visual cortical neurons to binocular disparity without depth perception. Nature *389*, 280–283.
9. Tong, F., Nakayama, K., Vaughan, J.T., and Kanwisher, N. (1998). Binocular rivalry and visual awareness in human extrastriate cortex. Neuron *21*, 753–759.
10. Tong, F., and Engel, S.A. (2001). Interocular rivalry revealed in the human cortical blind-spot representation. Nature *411*, 195–199.
11. Juan, C.H., Campana, G., and Walsh, V. (2004). Cortical interactions in vision and awareness: Hierarchies in reverse. Prog. Brain Res. *144*, 117–130.
12. Tong, F. (2003). Primary visual cortex and visual awareness. Nat. Rev. Neurosci. *4*, 219–229.
13. Bullier, J. (2001). Feedback connections and conscious vision. Trends Cogn. Sci. *5*, 369–370.
14. Silvanto, J., Lavie, N., and Walsh, V. (2005). Double dissociation of V1 and V5/MT activity in visual awareness. Cereb. Cortex *15*, 1736–1741.
15. Silvanto, J., Cowey, A., Lavie, N., and Walsh, V. (2005). Striate cortex (V1) activity gates awareness of motion. Nat. Neurosci. *8*, 143–144.
16. Barlow, H.B. (1972). Single units and sensation: A neuron doctrine for perceptual psychology? Perception *1*, 371–394.
17. Barlow, H.B. (1985). The twelfth Bartlett memorial lecture: The role of single neurons in the psychology of perception. Q. J. Exp. Psychol. A *37*, 121–145.
18. Pollen, D.A. (1999). On the neural correlates of visual perception. Cereb. Cortex *9*, 4–19.
19. Zeki, S., and Bartels, A. (1999). Toward a theory of visual consciousness. Conscious. Cogn. *8*, 225–259.
20. Goodale, M.A., and Milner, A.D. (1992). Separate visual pathways for perception and action. Trends Neurosci. *15*, 20–25.
21. Foerster, O. (1931). The cerebral cortex in man. Lancet *2*, 309–312.
22. Bartlett, J.R., DeYoe, E.A., Doty, R.W., Lee, B.B., Lewine, J.D., Negrao, N., and Overman, W.H., Jr. (2005). Psychophysics of electrical stimulation of striate cortex in macaques. J. Neurophysiol. *94*, 3430–3442.
23. Brindley, G.S., and Lewin, W.S. (1968). The sensations produced by electrical stimulation of the visual cortex. J. Physiol. *196*, 479–493.
24. Tehovnik, E.J., Slocum, W.M., Carvey, C.E., and Schiller, P.H. (2005). Phosphene induction and the generation of saccadic eye movements by striate cortex. J. Neurophysiol. *93*, 1–19.
25. Penfield, W. (1958). Some mechanisms of consciousness discovered during electrical stimulation of the brain. Proc. Natl. Acad. Sci. USA *44*, 51–66.
26. DeYoe, E.A., Lewine, J.D., and Doty, R.W. (2005). Laminar variation in threshold for detection of electrical excitation of striate cortex by macaques. J. Neurophysiol. *94*, 3443–3450.
27. Bartlett, J.R., and Doty, R.W. (1980). An exploration of the ability of macaques to detect microstimulation of striate cortex. Acta. Neurobiol. Exp. (Wars) *40*, 713–727.
28. Doty, R.W. (1965). Conditioned reflexes elicited by electrical stimulation of the brain in macaques. J. Neurophysiol. *28*, 623–640.
29. Green, D.M., and Swets, J.A. (1966). Signal Detection Theory and Psychophysics (New York: Wiley and Sons).
30. Tehovnik, E.J., Slocum, W.M., and Schiller, P.H. (2002). Differential effects of laminar stimulation of V1 cortex on target selection by macaque monkeys. Eur. J. Neurosci. *16*, 751–760.
31. Van Essen, D.C., Anderson, C.H., and Felleman, D.J. (1992). Information processing in the primate visual system: An integrated systems perspective. Science *255*, 419–423.
32. Pelli, D.G., Farell, B., and Moore, D.C. (2003). The remarkable inefficiency of word recognition. Nature *423*, 752–756.
33. Maunsell, J.H.R., and Cook, E.P. (2002). The role of attention in visual processing. Philos. Trans. R. Soc. Lond. B Biol. Sci. *357*, 1063–1072.
34. Amir, Y., Harel, M., and Malach, R. (1993). Cortical hierarchy reflected in the organization of intrinsic connections in macaque monkey visual cortex. J. Comp. Neurol. *334*, 19–46.
35. Yoshioka, T., Levitt, J.B., and Lund, J.S. (1992). Intrinsic lattice connections of macaque monkey visual cortical area V4. J. Neurosci. *12*, 2785–2802.
36. Elston, G.N., and Rosa, M.G. (1998). Morphological variation of layer III pyramidal neurones in the occipitotemporal pathway of the macaque monkey visual cortex. Cereb. Cortex *8*, 278–294.
37. Vogels, R., Saunders, R.C., and Orban, G.A. (1997). Effects of inferior temporal lesions on two types of orientation discrimination in the macaque monkey. Eur. J. Neurosci. *9*, 229–245.
38. De Weerd, P., Desimone, R., and Ungerleider, L.G. (2003). Impairments in spatial generalization of visual skills after V4 and TEO lesions in macaques (Macaca mulatta). Behav. Neurosci. *117*, 1441–1447.
39. Schmidt, E.M., Bak, M.J., Hambrecht, F.T., Kufta, C.V., O'Rourke, D.K., and Vallabhanath, P. (1996). Feasibility of a visual prosthesis for the blind based on intracortical microstimulation of the visual cortex. Brain *119*, 507–522.
40. 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.
41. Britten, K.H., and van Wezel, R.J. (1998). Electrical microstimulation of cortical area MST biases heading perception in monkeys. Nat. Neurosci. *1*, 59–63.

42. Ditterich, J., Mazurek, M.E., and Shadlen, M.N. (2003). Microstimulation of visual cortex affects the speed of perceptual decisions. Nat. Neurosci. *6*, 891–898.
43. Nichols, M.J., and Newsome, W.T. (2002). Middle temporal visual area microstimulation influences veridical judgments of motion direction. J. Neurosci. *22*, 9530–9540.
44. Cavanaugh, J., and Wurtz, R.H. (2004). Subcortical modulation of attention counters change blindness. J. Neurosci. *24*, 11236–11243.
45. Moore, T., and Fallah, M. (2004). Microstimulation of the frontal eye field and its effects on covert spatial attention. J. Neurophysiol. *91*, 152–162.
46. de Lafuente, V., and Romo, R. (2005). Neuronal correlates of subjective sensory experience. Nat. Neurosci. *8*, 1698–1703.
47. Van Essen, D.C. (2004). Surface-based approaches to spatial localization and registration in primate cerebral cortex. Neuroimage *23* (*Suppl 1*), S97–S107.
48. Zeki, S.M. (1978). The third visual complex of rhesus monkey prestriate cortex. J. Physiol. *277*, 245–272.
49. Quick, R.F., Jr. (1974). A vector-magnitude model of contrast detection. Kybernetik *16*, 65–67.