Reprinted from Nature, Vol. 346, No. 6280, pp. 174–177, 12th July, 1990

Cortical microstimulation influences perceptual judgements of motion direction

C. Daniel Salzman, Kenneth H. Britten & William T. Newsome*

Department of Neurobiology, Stanford University School of Medicine, Stanford, California 94305, USA

NEURONS in the visual cortex respond selectively to perceptually salient features of the visual scene, such as the direction and speed of moving objects, the orientation of local contours, or the colour or relative depth of a visual pattern. It is commonly assumed that the brain constructs its percept of the visual scene from information encoded in the selective responses of such neurons. We have now tested this hypothesis directly by measuring the effect on psychophysical performance of modifying the firing rates of physiologically characterized neurons. We required rhesus monkeys to report the direction of motion in a visual display while we electrically stimulated clusters of directionally selective neurons in the middle temporal visual area (MT, or V5), an extrastriate area that plays a prominent role in the analysis of visual motion information[1–8]. Microstimulation biased the animals' judgements towards the direction of motion encoded by the stimulated neurons. This result indicates that physiological properties measured at the neuronal level can be causally related to a specific aspect of perceptual performance.

Like other cortical sensory areas, MT is organized in a columnar fashion so that clusters of neighbouring neurons have similar physiological properties[9]. In MT, neurons in a single cortical column discharge a burst of action potentials in response to motion in a 'preferred' direction, but yield little or no response to motion in the opposite or 'null' direction. The preferred direction of motion varies systematically from column to column so that MT contains a complete representation of motion direction at each location in the visual field. Consequently, a microstimulation current that selectively elevates the discharge rate of a small cluster of MT neurons should enhance the intracortical signal related to a particular direction of motion. In primate motor cortex, a 10-μA pulse of cathodal current directly activates neurons within ~85 μm of the electrode tip[10]. To activate local clusters of MT neurons, we therefore applied 10 μA stimulating pulses (0.2-msec pulses, 200 Hz, biphasic) to selected sites in which neurons encountered over 150 μm of electrode travel had similar preferred directions. Although we attempted to confine direct excitation to a local cluster, neurons remote from the stimulation site were probably activated trans-synaptically[11]. But activation of remote neurons does not necessarily imply a loss of functional selectivity; there is increasing evidence that cortical columns are preferentially connected with other columns having similar response properties[12,13]. These considerations suggest that microstimulation in our experiments may have activated a circuit of neurons encoding a particular direction of motion.

Our methods for electrophysiological recording and for monitoring eye movements in trained rhesus monkeys were adapted from those of Wurtz and colleagues[14,15], and our psychophysical methods were based on those described by Newsome and Paré[6]. Figure 1 illustrates the procedures used in the present experiments. In brief, three rhesus monkeys were trained to discriminate the direction of motion in a random dot display shown on a video screen. In the display, a specifiable percentage of the dots carried a constant-velocity or 'correlated' motion signal while the remaining dots moved in random directions, creating a masking motion noise. We varied the strength of the motion signal by changing the percentage of dots in

* To whom correspondence should be addressed.

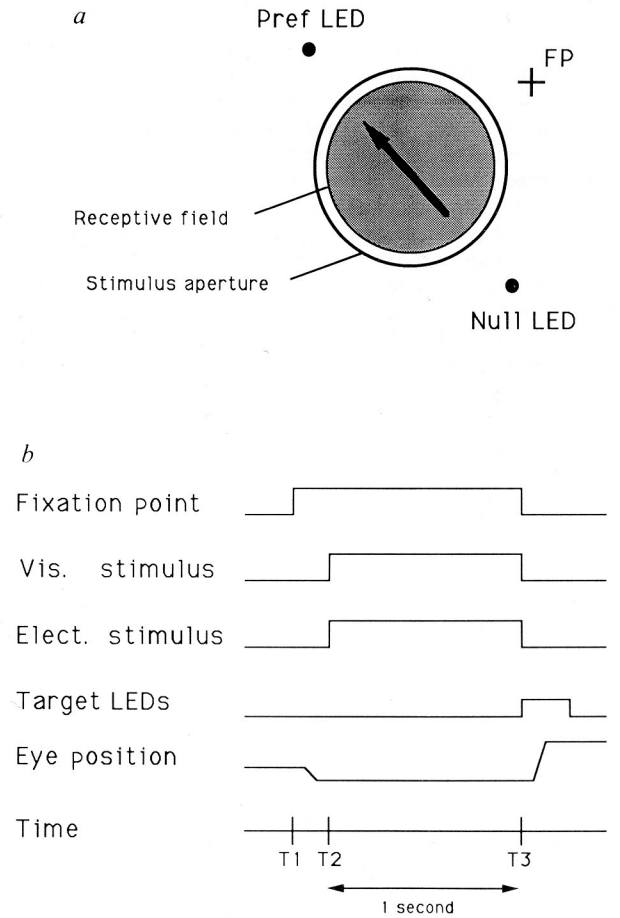

FIG. 1 The experimental protocol used to measure the effect of microstimulation on perceptual judgements of motion direction. *a*, Schematic diagram showing the spatial arrangement of the fixation point (FP), receptive field (shaded), stimulus aperture (thick circle) and response light emitting diodes (LEDs). While the monkey centred its gaze on the fixation point, we mapped the receptive field and identified the preferred direction (arrow) and speed of motion of neurons at the stimulation site. The random dot motion display was presented within a circular aperture whose dimensions and location were matched to those of the multi-neuron receptive field, and the speed of the motion signal was set equal to the preferred speed of the neurons. On a given trial, the motion signal in the visual display was randomly selected to be in the neurons' preferred direction (arrow) or in the null direction (opposite to arrow). The strength of the motion signal was randomly varied among four possible correlation levels: 0% correlation or one of three levels near psychophysical threshold. The monkey viewed the visual display for one second while maintaining its gaze on the fixation point. After the viewing interval, the monkey indicated its choice of motion direction by making a saccadic eye movement to one of two light emitting diodes (Pref LED and Null LED) that corresponded to the two possible directions of motion. Note that in all respects the visual display was tailored so that the demands of the psychophysical task were well matched to the information supplied by the neurons at the stimulation site. Since we tailored the visual display in this manner at each stimulation site, the spatial arrangement of the receptive field, stimulus aperture, preferred–null axis of motion, and response LEDs varied considerably from site to site. *b*, Schematic drawing illustrating the temporal sequence of events during a microstimulation trial. At time T1 the fixation point appeared and the monkey transferred its gaze to the fixation point, as indicated by the deflection in the eye position trace. At time T2 the visual (Vis.) stimulus appeared and the train of electrical (Elect.) stimulation pulses began. The monkey was required to maintain fixation for one second until time T3; if the monkey broke fixation during this interval the trial was aborted. The fixation point, visual stimulus and microstimulation pulses were turned off at time T3, and the target LEDs turned on. The monkey then indicated its judgement of motion direction by making a saccadic eye movement to one of the two response LEDs. A liquid reward was given for a correct choice, and an incorrect choice was penalized with a brief 'time-out' period. Unstimulated trials differed only in that no electrical stimulation accompanied the visual stimulus. The reward contingencies were identical for trials with and without stimulation.

correlated motion. For each experiment a new stimulation site was selected and the motion display was placed in the multineuron receptive field mapped at the stimulation site. On a given trial the monkey maintained visual fixation on a stationary point of light while viewing the random dot stimulus for one second. The correlated motion signal was randomly selected to be in either the preferred or null direction of the local cluster of neurons. After the viewing interval, the monkey indicated its judgement of motion direction by making a saccadic eye movement to one of two light-emitting diodes corresponding to the possible directions of the motion stimulus. The monkey received a liquid reward for a correct choice. An experiment consisted of 640 randomly interleaved trials. On half of the trials we applied electrical stimulation that began and ended simultaneously with the onset and offset of the random dot stimulus. The monkeys performed trials at four correlation levels—0% correlation and three levels near psychophysical threshold. The reward contingencies were identical on stimulated and nonstimulated trials.

If microstimulation enhances the intracortical signal related to the preferred direction of motion of the local cluster of neurons, we would expect stimulation to bias the animal's psychophysical judgements towards that direction. Figure 2 shows the results of two experiments in which microstimulation had such an effect. For both experiments, the proportion of decisions in favour of the preferred direction ('preferred decisions') is plotted against the strength of the motion signal expressed as the percentage of dots in correlated motion. The closed symbols represent trials with electrical stimulation; open symbols correspond to nonstimulated trials. Positive correlations indicate motion in the preferred direction and negative correlations represent motion in the opposite direction. Comparing performance on stimulated and nonstimulated trials, one can see that at every correlation level the monkey made more preferred decisions when electrical stimulation accompanied the visual stimulus, with a net increase of 43 preferred decisions in Fig. 2*a* and 118 preferred decisions in Fig. 2*b*.

In both experiments of Fig. 2, the increase in preferred decisions due to microstimulation can be described as a leftward shift of the psychometric function. The magnitude of the leftward shift quantifies the microstimulation effect in units of the visual stimulus. In other words, the magnitude of the leftward shift, expressed as percentage of correlated dots, corresponds to the visual stimulus change that would mimic the behavioural effect of microstimulation. We employed logistic regression analysis[16] to measure the magnitude and statistical significance of the stimulation-induced shift of the psychometric function. For the experiment of Fig. 2*a*, the effect of microstimulation was behaviourally equivalent to the addition of 7.7% correlated dots to the visual stimulus and was highly significant ($P \leq 0.0001$). For the much larger effect in Fig. 2*b*, the effect of microstimulation was behaviourally equivalent to the addition of 20.1% correlated dots ($P \leq 0.0001$).

Microstimulation caused statistically significant shifts in the psychometric function ($P < 0.05$) in 18 of 38 experiments in one monkey, in 9 of 16 experiments in a second monkey, and in 3 of 8 in a third. Figure 3 shows for each experiment the magnitude of the stimulation-induced shift expressed as percentage of correlated dots. Positive values correspond to leftward shifts in the psychometric function and negative values correspond to rightward shifts. Striped bars indicate experiments in which the shift of the psychometric function was statistically significant. In 29 of the 30 experiments that yielded significant effects, microstimulation shifted the psychometric function leftwards, indicating an increase in preferred decisions. In the remaining experiment, microstimulation caused a highly significant rightward shift, an observation that could be explained if microstimulation had a large effect on nearby columns whose preferred direction was opposite to that of the target column. This is a plausible explanation for the single counterintuitive result as adjacent columns of MT neurons sometimes have opposite preferred directions[9].

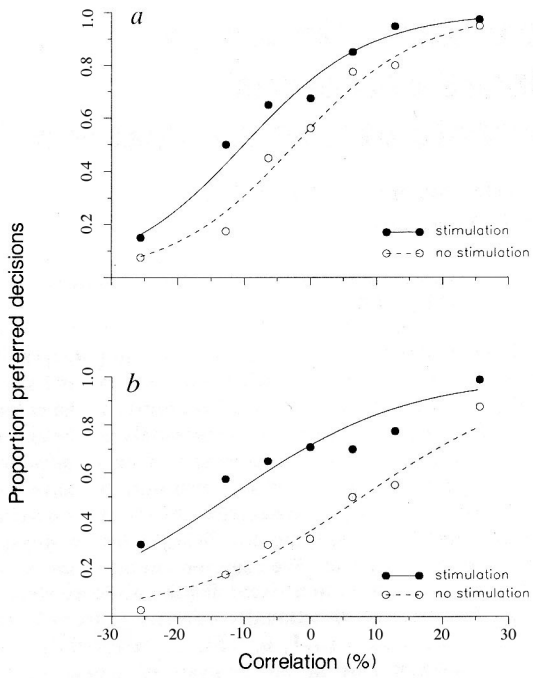

FIG. 2 Effect of microstimulation on psychophysical performance for two stimulation sites in MT. The abscissa indicates the strength of the motion signal in percentage of correlated dots. Positive correlation values indicate motion in the neurons' preferred direction; negative values correspond to motion in the opposite—'null'—direction. The ordinate shows the proportion of trials in which the monkey judged motion to be in the preferred direction of the stimulated neurons (preferred decision). Each data point is based on 40 trials, except for 0% correlation for which 80 trials were conducted. The correlation levels were selected so that the monkey would judge the direction of motion correctly in ~70% of the trials in a block. In half the trials (●) microstimulation was applied simultaneously with the visual stimulus; the other trials (○) contained no microstimulation. For each experiment we employed logistic regression analysis[16] to fit sigmoidal curves of equal slope to the stimulated and nonstimulated data; the curves thus derived provided an acceptable fit to most of the data. *a*, Typical experiment in which stimulation biased the monkey's perceptual decisions towards the preferred direction of the stimulated neurons. The psychometric function for the stimulated trials was shifted leftwards by 7.7% correlated dots. The magnitude of the shift indicates that the behavioural effect of microstimulation could have been reproduced by adding to the visual stimulus 7.7% correlated dots in the preferred direction. *b*, Experiment in which microstimulation induced a leftward shift of 20.1% correlated dots, one of the larger effects we observed. The different appearance of the 'no stimulation' curves in *a* and *b* resulted largely from differences in choice bias in the two experiments. In the no stimulation condition in *a*, the monkey favoured the preferred direction on 56% of the trials at 0% correlation. Note that with no choice bias, the monkey would have made 50% preferred decisions at 0% correlation; in this experiment, therefore, the monkey had a very small choice bias. In the no stimulation condition in *b*, however, the monkey made preferred decisions on only 33% of the trials at 0% correlation. In this experiment, the monkey had a pronounced bias towards the null direction response LED; the effects of this bias are evident at other points on the no stimulation curve as well. Choice bias is a common phenomenon in human and animal psychophysics, and its presence and intensity in any particular experiment is difficult to predict. Most bias values observed in the present experiments were within the range observed in previous experiments that did not involve electrical microstimulation.

The data in Fig. 3 show that microstimulation biased the monkeys' perceptual decisions towards the preferred direction of the stimulated neurons. The result is consistent with the notion that focal microstimulation enhances the sensory representation of one direction of motion relative to others. An alternative explanation, however, is that microstimulation had a direct effect on the operant response, a saccadic eye movement. The latter hypothesis seems unlikely for several reasons. First, physio-

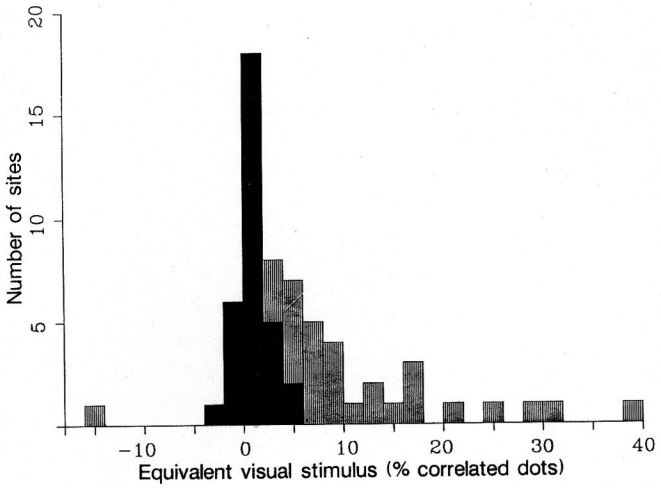

FIG. 3 Frequency histogram showing the magnitude of the stimulation-induced shift in the psychometric function for 62 experiments in three monkeys. The shift in the psychometric function may be thought of as an 'equivalent visual stimulus'—the visual stimulus change that would mimic the behavioural effect of microstimulation. Positive values indicate leftward shifts of the psychometric function; negative values indicate rightward shifts. The striped bars identify experiments in which the effect of microstimulation was statistically significant (logistic regression $P<0.05$). In 29 of the 30 experiments with statistically significant effects, the stimulation-induced shift was leftwards, indicating an increase in decisions favouring the preferred direction of the stimulated neurons.

logical recordings made during saccadic eye movements have failed to find any evidence of motor signals in MT[17]. Second, lesions of MT have no effect on saccades to stationary targets[18]. Third, control experiments show that microstimulation applied during the intertrial interval has no effect on eye movements. Finally, the long latency (>1 s) between the onset of microstimulation and execution of the saccade argues against a direct effect of stimulating current on motor signals. We therefore consider it highly probable that microstimulation affected the sensory signals underlying perceptual judgements of motion direction rather than motor signals related to the saccadic eye movement *per se*.

As the multi-unit receptive field at a given microstimulation site occupies a small portion of the visual field, it is desirable to know whether the perceptual effects of microstimulation are similarly localized in visual space. To answer this question, we required a monkey to perform the psychophysical task in the usual manner, but applied microstimulation to a topographically noncorresponding site in MT. In these experiments there was no overlap betwen the visual display aperture and the receptive field at the stimulation site. The effect of microstimulation was greatly attenuated or eliminated under these conditions. Thus the microstimulation effects were correlated with the spatial location, as well as the preferred direction, of the receptive field of the stimulated neurons.

Given the complexity of primate visual cortex, which contains more than 20 different visual areas with multiple anatomical interconnections, it is remarkable that local microstimulation of directionally selective neurons can cause a substantial change in psychophysical performance. This result may be less surprising if, as we suggested above, microstimulation trans-synaptically activates an extended circuit of neurons. This amplification of neuronal signals could be accomplished by activation of nearby columns in MT having a similar preferred direction and receptive field location, or by activation of similarly tuned neurons in visual areas other than MT. Although we do not know the full extent of cortex affected by microstimulation, the demonstrated correlation between neuronal preferred direction and psychophysical choice suggests that the activated neurons were functionally related to a particular direction of motion. The data therefore provide evidence causally relating neuronal activity to perceptually judged direction of motion. This experimental approach, which combines electrical microstimulation with multi-neuron physiological analysis and an appropriate perceptual task, may also prove useful for investigating cortical circuits that contribute to other aspects of visual perception such as orientation, colour and depth. □

Received 5 February; accepted 27 April 1990.

1. Dubner, R. & Zeki, S. M. *Brain Res.* **35,** 528–532 (1971).
2. Zeki, S. M. *J. Physiol.* **236,** 549–573 (1974).
3. Baker, J. F., Petersen, S. E., Newsome, W. T. & Allman, J. M. *J. Neurophysiol.* **45,** 397–416 (1981).
4. Maunsell, J. H. R. & Van Essen, D. C. *J. Neurophysiol.* **49,** 1127–1147 (1983).
5. Albright, T. D. *J. Neurophysiol.* **52,** 1106–1130 (1984).
6. Newsome, W. T. & Paré, E. B. *J. Neurosci.* **8,** 2201–2211 (1988).
7. Siegel, R. M. & Andersen, R. A. *Soc. Neurosci. Abstr.* **12,** 1183 (1986).
8. Newsome, W. T., Britten, K. H. & Movshon, J. A. *Nature* **341,** 52–54 (1989).
9. Albright, T. D., Desimone, R. & Gross, C. G. *J. Neurophysiol.* **51,** 16–31 (1984).
10. Stoney, S. D., Jr., Thompson, W. D. & Asanuma, H. *J. Neurophysiol.* **31,** 659–669 (1968).
11. Jankowska, E., Padel, Y. & Tanaka, R. *J. Physiol.* **249,** 617–636 (1975).
12. Ts'o, D. Y. & Gilbert, C. D. *J. Neurosci.* **8,** 1712–1727 (1988).
13. Gilbert, C. D. & Wiesel, T. N. *J. Neurosci.* **9,** 2432–2442 (1989).
14. Mikami, A., Newsome, W. T. & Wurtz, R. H. *J. Neurophysiol.* **55,** 1308–1327 (1986).
15. Komatsu, H. & Wurtz, R. H. *J. Neurophysiol.* **62,** 31–47 (1989).
16. Cox, D. R. *Analysis of Binary Data* (Methuen, London, 1970).
17. Newsome, W. T., Wurtz, R. H. & Komatsu, H. *J. Neurophysiol.* **60,** 604–620 (1988).
18. Newsome, W. T., Wurtz, R. H., Dürsteler, M. R. & Mikami, A. *J. Neurosci.* **5,** 825–840 (1985).

ACKNOWLEDGEMENTS. We are grateful to J. A. Movshon and M. Shadlen for their contributions to this project, and to several colleagues who provided critical comments on the manuscript. The work was supported by the National Eye Institute, the Office of Naval Research, and by a McKnight Development Award to W.T.N. C.D.S. is supported by a Medical Student Research Training Fellowship from the Howard Hughes Medical Institute.