Pergamon

PII: S0042-6989(96)00256-8

Vision Res., Vol. 37, No. 7, pp. 853–863, 1997

Printed in Great Britain
0042-6989/97 $17.00 + 0.00

Visual Responses of Neurons from Areas V1 and MT in a Monkey with Late Onset Strabismus: A Case Study

A. THIELE,*‡ F. BREMMER,* U. J. ILG,*† K.-P. HOFFMANN*

Received 6 July 1994; in revised form 9 April 1996

One adult monkey (*Macaca fascicularis*) was investigated psychophysically and electrophysiologically after at least 5 years of late onset esotropic macrostrabismus (squint angle 52 deg). Behavioural tests revealed normal monocular visual and visuomotor functions. No indications of deep amblyopia or oculomotor asymmetry were found. The monkey used the left or right eye alternately at about equal frequencies. Single unit recordings from area V1 disclosed a normal ocular dominance distribution. Most V1 neurons from both hemispheres received binocular input. Thus, discordant visual information from corresponding retinal locations of the two eyes converged onto the cortical neurons. No evidence for anomalous retinal correspondence was found. Diplopia and confusion must therefore be avoided by suppression of vision through one eye to allow stable, unambiguous perception. Possible suppression was investigated by stimulating a neuron through the same eye when it was actively used for fixation in one set of trials, and when it was not used for fixation in another set of trials. Significant differences in these two stimulus conditions were found in 20/39 neurons from area V1 and in 11/34 motion sensitive neurons recorded in the middle superior temporal area (MT). The normalized population activity in V1 and MT was higher if cells were stimulated through the fixating eye. The data are discussed with respect to possible suppressive mechanisms helping to prevent double vision in strabismus and in binocular rivalry.

Strabismus Binocular rivalry Striate cortex MT

INTRODUCTION

Esotropic strabismus occurring during a sensitive period of postnatal development leads to manifold changes in the visual system. A loss of binocular vision in cats and monkeys is caused by a dramatic shift of ocular dominance in striate cortex cells outside layer IV (Hubel, 1979; Wiesel, 1982; Hoffmann & Schoppmann, 1984; Boothe *et al.*, 1985; Kiorpes, 1989). Esotropic congenital or experimentally induced strabismus can often lead to deep amblyopia in one eye (Kalil *et al.*, 1984; Boothe *et al.*, 1985; Kiorpes, 1989). As a consequence, strabismic amblyopes often show deficits in smooth pursuit eye movements (Tychsen & Lisberger, 1986; Bedell *et al.*, 1990), they exhibit optokinetic asymmetries (Demer & von Noorden, 1988; Aiello *et al.*, 1994; Kommerell *et al.*, 1995), deficits concerning spatial and contrast sensitivity (Kiorpes, 1989; Kiorpes & Movshon, 1989), they often have problems in controlling eye position (Schor & Hallmark, 1978), and may have reduced sensitivity in the nasal visual field of the amblyopic eye (Sireteanu, 1982a; Kiper & Kiorpes, 1994). In esotropic humans, anomalous retinal correspondence may be developed to some degree (Sireteanu, 1982b; Sireteanu & Fronius, 1989). This may help to have binocular fusion and the two images of an object give rise to a single sensation despite the misalignment of the eyes. These deficits and changes cannot be found if strabismus occurs after the sensitive period. In these cases, discordant information from corresponding retinal locations is combined in binocular neurons of area V1, or higher cortical areas. Unless some mechanisms are evolved to suppress information from the eye which is currently not used for fixation, two independent pictures of the external world would be perceived. These circumstances are comparable to binocular rivalry, a phenomenon which occurs if corresponding parts of the two retinae are stimulated with different patterns or objects. This different stimulation leads to false binocular fusion (Blake, 1989), but instead of seeing both stimuli, the perception of one of the two is suppressed during phases of rivalry (Levelt, 1965;

*Allg. Zoologie and Neurobiologie, Ruhr Universität Bochum, 44780 Bochum, Germany.

†Present address: Neurologische Universitätsklinik, Hoppe-Seylerstr. 3, 72076 Tübingen, Germany.

‡To whom all correspondence should be addressed [*Tel* +49 234 700 4369; *Fax* +49 234 709 4278; *Email* thiele@neurobiologie.ruhr-uni-bochum.de].

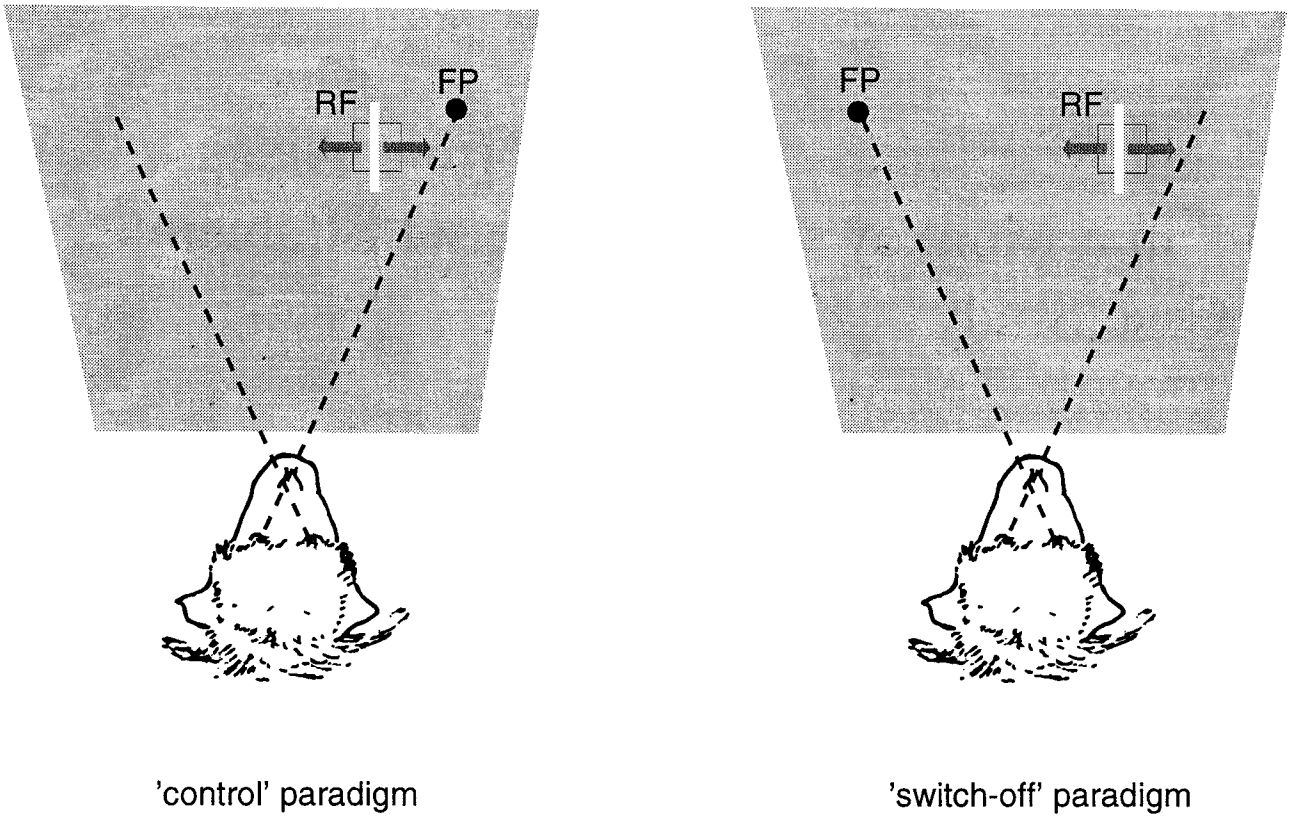

FIGURE 1. The monkey was trained to fixate a spot (fixation point, FP) 25 deg to the left or to the right of the centre of the screen with its right or left eye, respectively. First the cell activity was determined with stimulation through the fixating eye. Next the monkey was instructed to fixate the spot now shifted 50 deg across his nose with the other eye. The stimulus was "clamped" to the RF of the now non-fixating eye (see Methods). Due to the squint angle the now non-fixating eye largely remained in its original position. The cell's activity was then recorded while stimulated through the non-fixating eye. Both paradigms were repeated with 20–30 trials, two to three times for each eye.

Blake, 1989; Logothetis & Schall, 1989; Leopold & Logothetis, 1996).

As the monkey in our experiment showed normal ocular dominance distribution for cells in area 17 and psychophysical tests gave no hint of deep amblyopia, it seemed an adequate model to investigate the transmission and suppression of discordant information in visual cortical areas V1 and MT.

METHODS

Areas V1 and MT were analysed in an adult, strabismic, behaving monkey (*Macaca fascicularis*) by single unit recordings. After appropriate training, recording chambers, scleral search coils and a head holder were implanted under pentobarbital anaesthesia prior to the experiments. During the experiments the monkey was comfortably seated in a chair with head restrained. Anaesthesia during surgery and animal care during experiments was carried out according to the guidelines of the European Community (EUVD 86/609/EEC) and the American Physiological Society. The animal was trained to fixate a small spot of light (0.4 cd/m^2) on a translucent screen (90 deg × 90 deg in extent). During fixation a second optimized stimulus (1.2 cd/m^2) was presented to analyse the receptive field. Computer controlled movement of the fixation point permitted analysis of saccade or smooth pursuit eye movements. Correct fixation was rewarded with a drop of apple juice. To obtain a clue whether the onset of strabismus had occurred during the sensitive period or later, appropriate behavioural measurements were conducted prior to the single cell recording experiments.

1. Optokinetic nystagmus was elicited by projecting random dot stimuli or square wave gratings onto the translucent screen. Stimulus velocity (1–64 deg/sec) and stimulus direction were computer controlled via galvanometers.
2. Smooth pursuit eye movements were tested in a step ramp paradigm.
3. Saccade accuracy was tested by randomly presenting a target at eccentricities ±15, ±20, ±25, ±27.5, ±30 deg, along the horizontal meridian. Whenever the monkey failed to foveate the target within 300 msec, another target was presented.
4. Frequency of alternation was investigated by randomly presenting a target at eccentricities 15, 20, 25, 27.5, 30 and 32 deg into the temporal visual

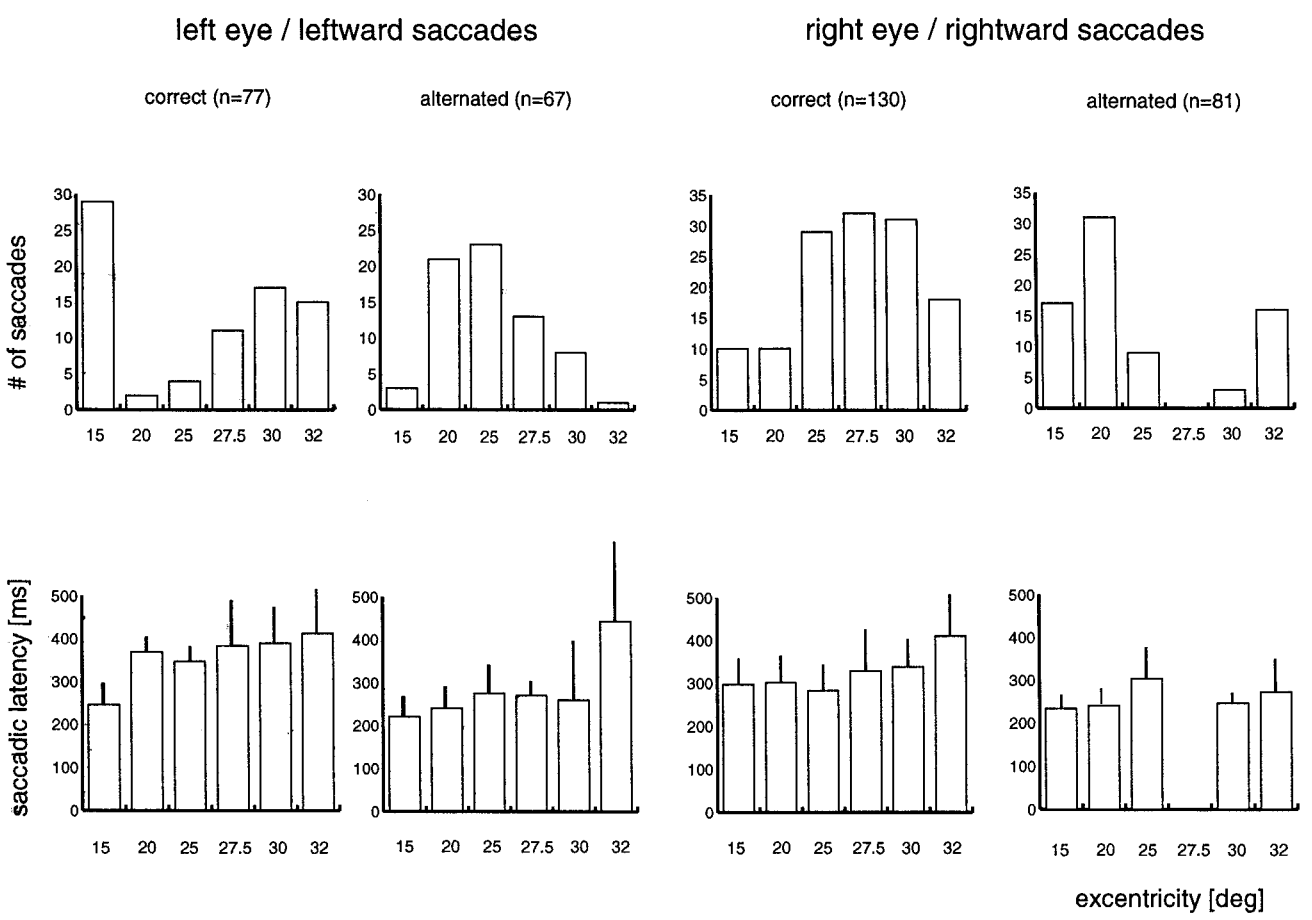

FIGURE 2. Frequency distribution (upper histograms) and latencies (lower histograms) of saccades to targets with different eccentricities from the fovea of the fixating eye. Abscissa: eccentricity in degrees of visual angle (deg); ordinate: number of saccades (upper) or latency in msec (lower histograms).

field of the fixating eye. Saccades brought the fovea of either the fixating or the deviated eye to the new target.

In order to reveal whether the activity of a given neuron is different when the monkey switches fixation from one eye to the other, we designed the "control" and the "switch-off" paradigms (Fig. 1). In the "control" paradigm, the monkey was instructed to fixate a spot of light (FP) 25 deg to either the right or the left from the screen centre, with the left or right eye, respectively. The cell's activity was recorded while sweeping an optimized stimulus across the receptive field (RF) of the fixating eye. During the "switch-off" paradigm the monkey now fixated with the other eye. This was achieved easily by switching the eye position control window and presenting the fixation light to the other eye's fovea. Now the cell activity was recorded while stimulated through the non-fixating eye which remained in an almost identical orbital position. During both paradigms the position signal of the stimulated eye was superimposed onto the position signal for the stimulus. This ensured stimulation of identical retinal locations (cell's RF) despite slight deviations of eye position. Cell responses were recorded for typically 20–30 stimulus sweeps, and both paradigms were repeated at least twice, if possible three times.

Data analysis

Owing to the motion of the stimulus the cell activity was recorded during two different periods:

1. A period while the monkey actively fixated, but the stimulus was not yet moving through the receptive field. This period will be referred to as spontaneous activity.
2. The activity while the stimulus moved through the cell's receptive field was taken as the stimulus period.

At the single trial level the cells activity was analysed separately for both test conditions and for both activity periods (i.e., stimulus and spontaneous activity). A Kolmogorov–Smirnov test was applied to these data to see whether the activity during the switch-off paradigm was significantly different to the activity during the control paradigm. This was done for spontaneous activity and stimulus-related activity separately.

An activity difference index (ADI) was calculated for each cell for spontaneous and stimulus related activity.

$$\mathrm{ADI} = \frac{(\text{'control' activity} - \text{'switch-off' activity})}{(\text{'control' activity} + \text{'switch-off' activity})}$$

The mean ADI was calculated for each area, representing a normalized population activity difference.

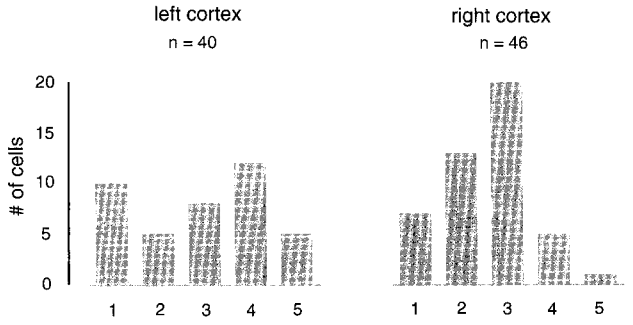

FIGURE 3. Ocular dominance distributions for neurons recorded in the left and right cortical area V1. Ordinate: number of cells; Abscissa: ocular dominance groups; 1 or 5: cells dominated exclusively by either the contra- (1) or ipsilateral eye (5); 2 or 4: cells with input from both eyes but still dominated by either the contra- or ipsilateral eye; 3: cells with approximately equal strength input from the two eyes. In the left cortex, cells belonging to one of the five cell classes are nearly equally distributed ($n = 40$). A dominance for one eye is not detectable, but cells with input of equal strength from both eyes (class 3) are not very prominent. In the right cortex ($n = 46$) most cells belong to class 3. A tendency for a stronger input from the left eye can be detected. The results do not indicate effects found in animals with early onset of strabismus.

After conversion to the standard normal deviate Z, a two-tailed t-test was applied to see whether the ADI population mean was significantly different from zero.

To analyse the relationship between the ADI values and the degree of binocularity for V1 neurons, an ocular dominance index (ODI) for each cell was calculated:

$$\mathrm{ODI} = \frac{(\mathrm{activity}_{\mathrm{left\ eye}} - \mathrm{activity}_{\mathrm{right\ eye}})}{(\mathrm{activity}_{\mathrm{left\ eye}} + \mathrm{activity}_{\mathrm{right\ eye}})}$$

RESULTS

Psychophysics

Monocular OKN stimulations resulted in symmetrical gains for ipsi- and contraversive stimulation, which is a typical behaviour found in normal non-strabismic primates. Smooth pursuit eye movements also appeared normal when compared to non-strabismic animals. The monkey showed no deficits in gain in any direction of eye movement. Six hundred correct trials were performed with each eye during the saccade perimetry test. With one exception saccadic behaviour was normal. The monkey was not able to foveate low intensity targets (~ 0.4 cd/m^2) more than 15 deg left from the vertical meridian with its left eye within 300 msec. Instead he preferred to use the other (right) eye to foveate the saccade target. Saccade latencies were slightly longer for the left than for the right eye. These differences were not significant, (Students t-test, $P > 0.05$). The frequency of alternation and the respective saccadic latencies are shown in Fig. 2. For both eyes presentation of the saccade target was between the two foveae. Therefore, the monkey often used the eye to fixate the saccade target that previously was not fixating the fixation point. The monkey was rewarded if he fixated the saccade target with either eye. The upper histograms show the number of saccades that were performed to different eccentricities with respect to the previously fixating eye (correct: target was fixated with the eye that previously fixated the fixation point; alternated: saccade target was fixated with the eye that previously was not fixating the fixation point). For both eyes a range of eccentricities of saccadic targets was found that most often resulted in alternation.

This range slightly differed for the two eyes. The lower histograms display the latencies until a saccade was performed. Saccadic latencies were shorter when the monkey alternated, as compared to saccadic latencies performed with the previously fixating eye. From the figure, it is clear that the monkey used both eyes for fixation. The behavioural measurements did not indicate major oculomotor asymmetry or deep amblyopia.

Electrophysiology

Recordings from area V1 from both hemispheres were performed to investigate the ocular dominance distribution. We tried to obtain an unbiased sample of cells. Therefore, the electrode was advanced at least 150 μm every time a single unit had been investigated. Forty-six single units were recorded from the left cortex, and 40 from the right cortex.

Figure 3 shows the ocular dominance distribution from V1 of the left and right hemisphere. Binocular cells were found throughout all layers, except layer IV. Outside layer IV no tendency for a clustering or local dominance of monocular cells was found. Cells responded well to moving bars (minimum size: 0.5 deg $\times$ 1.0 deg), while they were stimulated through the fixating eye. Stimulus direction, speed, and size were optimized before performing the control and switch-off tests. The eye that is used for fixation will always be regarded as the "attentive eye".

The responses of 39 binocular cells from the right hemisphere of V1 were investigated during the switch-off and control paradigm. First both paradigms were done with one eye. If the cell was still well isolated after these trials, tests were carried out with the other eye as well. Sixteen of thirty-nine cells had parafoveal receptive fields (RF, within the central 5 deg of the visual field), but none of the RFs included the fovea itself. The remaining 23 cells had peripheral receptive fields.

Figure 4(A–C) shows the activity profiles of three V1 neurons while a bar was moving through the receptive field under the two paradigms (stimulus activity profiles: between the arrows). Additionally the activity was obtained while the bar was moving outside the receptive field (spontaneous activity profiles outside the arrows). In Fig 4(A) and (B) the activity was significantly different under the two stimulus conditions. This was not the case for the example shown in Fig. 4(C). There were no significant differences for spontaneous activity in any of the cells shown here.

V1 cells with parafoveal RFs

Significant activity differences were found in 3/14 cells, when stimulated through the right eye [Fig. 5(B)].

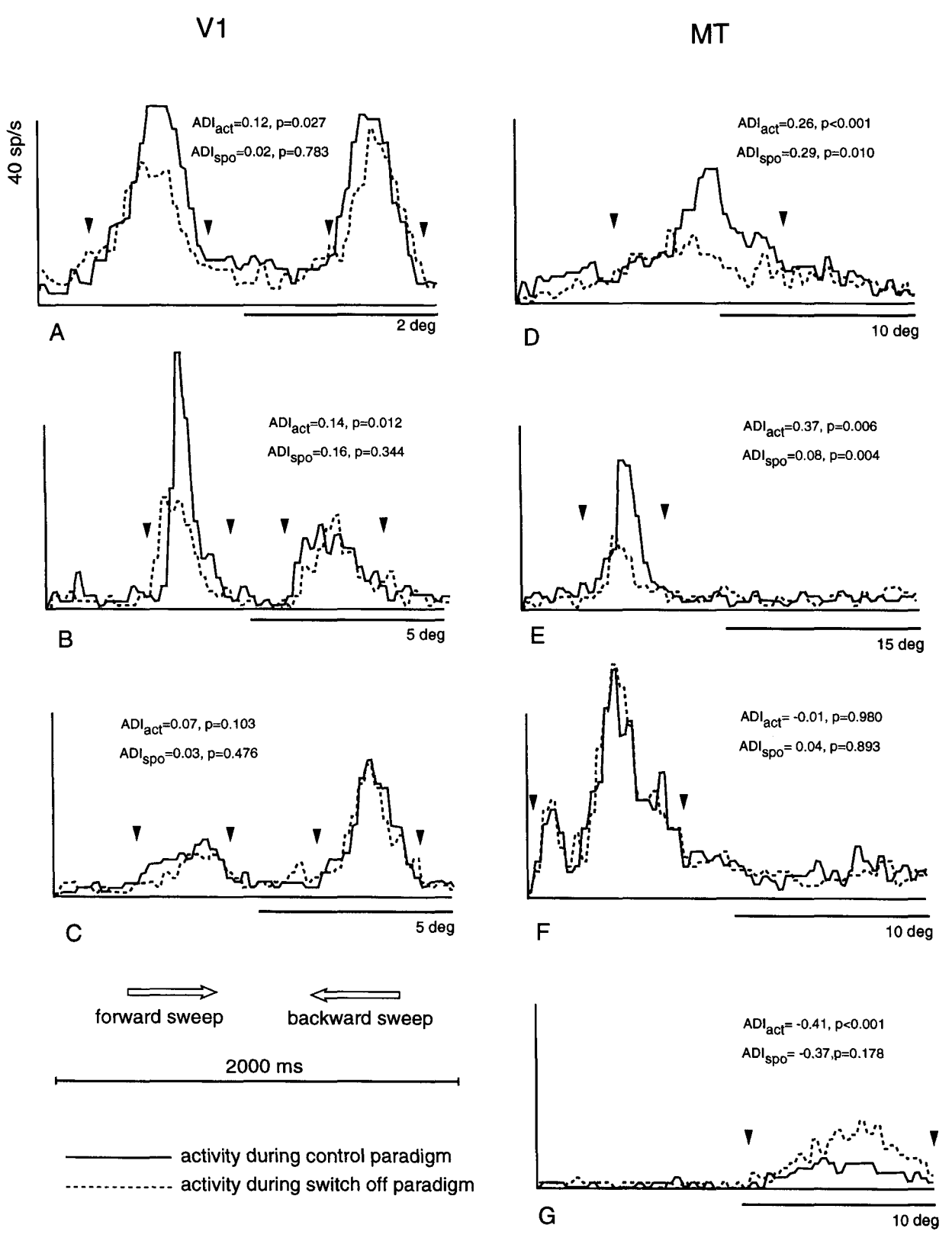

FIGURE 4. Activity profiles of cell responses under the control paradigm (solid line) and the switch-off paradigm (broken line). In between the arrows, the time period (msec) which was taken as stimulus related activity is indicated (first period: activity during forward sweep; second period: activity during backward sweep). The ordinate indicates the mean activity (spikes per second) within 40 msec bins. Below each abscissa the sweep amplitude is indicated, each bar represents 1 sec. Inset: the respective ADI values, and their significance is given in each figure. (A) and (B) show examples of V1 neurons with significantly higher activity under the control paradigm. (C) shows an example of a V1 neuron where no significant differences were found. (D–G) Activity profiles of MT neurons. In (D) and (E) significantly higher activity occurred during the control paradigm. No differences were found for the cell shown in (F). An example of significantly higher activity during the switch-off paradigm is shown in (G).

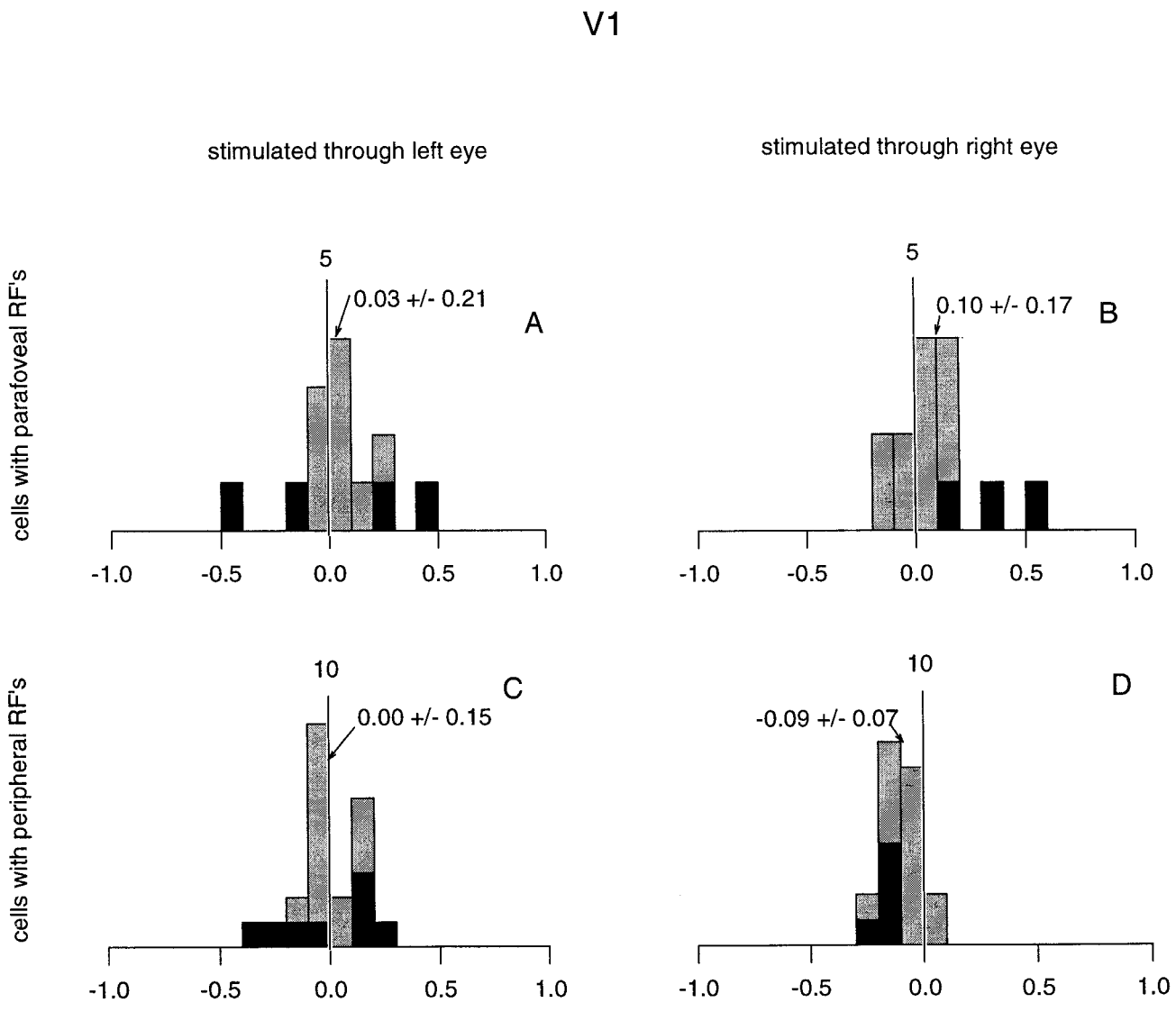

FIGURE 5. Distribution of activity difference indices for cells from V1. Positive values indicate that activity was higher during the control paradigm, negative values indicate that activity was higher during the switch-off paradigm. Solid black bars indicate the number of neurons with significant activity differences under the two paradigms. The population mean and its standard deviation is given as an inset in each histogram. Main differences during the stimulation period were found when cells were stimulated through the right eye. While the activity in cells with parafoveal RFs was usually higher during the control paradigm (B), cells with peripheral RFs showed the inverse behaviour (D). The population mean was close to zero, if cells were stimulated through the left eye (A, C).

In these cells the activity was always higher while the cell was stimulated through the *attentive eye*. The calculated ADI population mean was 0.10 ± 0.17 (an ADI value of 0.1 corresponds to a response reduction of 18.1%). This mean was found to be significantly different from zero ($P < 0.05$). The ADI population mean for spontaneous activity was 0.02 ± 0.20 (not significantly different from zero, $P > 0.05$).

If cells were stimulated through the left eye activity differences were significant in four cases [4/13, Fig. 5(A), in one of these cells significant differences were also found when stimulated through the right eye]. In two of these cases the activity was higher during the control, in the other two cases it was higher during the switch-off paradigm. The ADI population mean was 0.03 ± 0.21, corresponding to a response reduction of 9.7% ($P > 0.05$). This indicates that the population activity level is still slightly higher if stimulated through the *attentive eye*. Spontaneous activity was lower if the left eye was used for fixation (-0.08 ± 0.22; not significantly different from zero).

V1 cells with peripheral RFs

If cells were stimulated through the right *attentive eye*, responses to the stimulus were almost always *smaller* as compared to the switch-off paradigm [Fig. 5(D)]. In five cells these differences were significant, all exhibiting higher activity during the switch-off paradigm. The population mean is -0.09 ± 0.07 ($P < 0.05$). The effect of higher activity during the switch-off paradigm occurred also with spontaneous activity (-0.07 ± 0.23, $P > 0.05$).

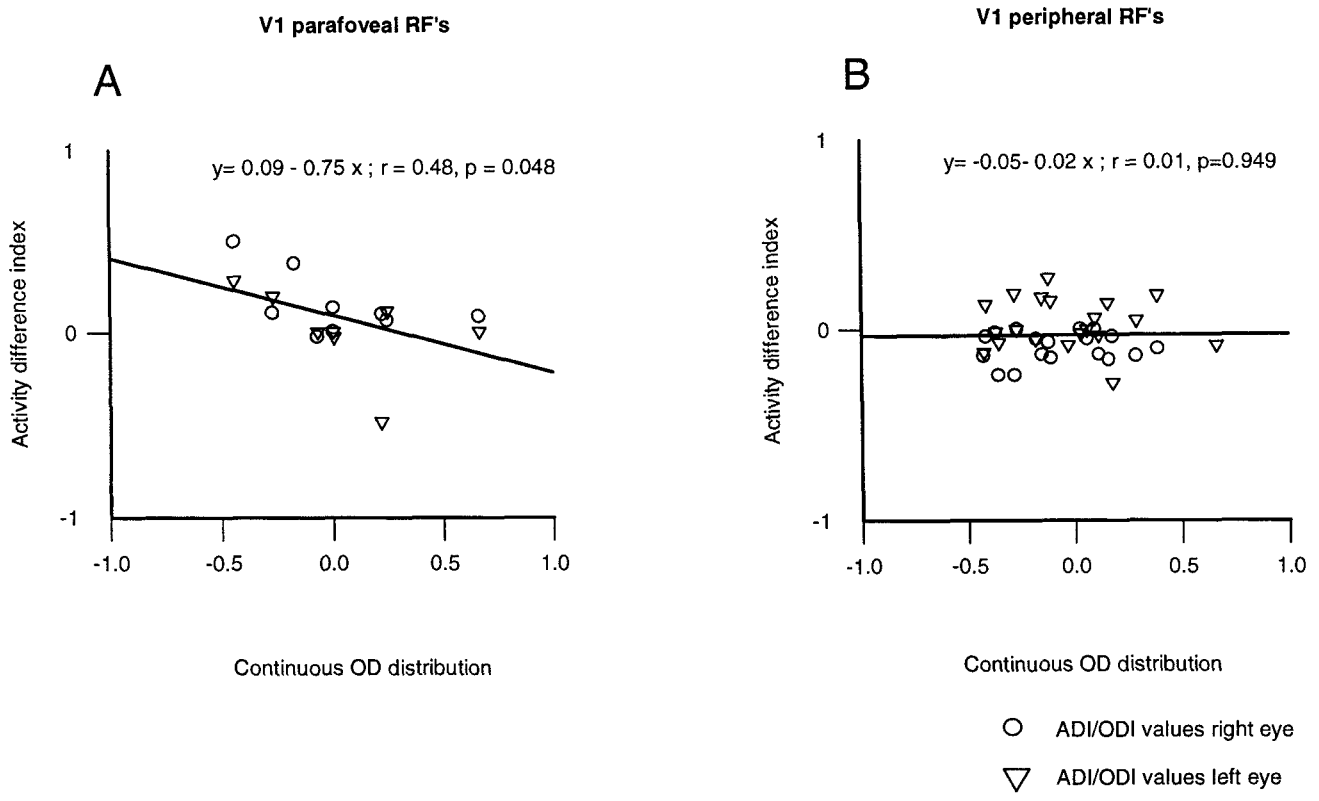

FIGURE 6. Correlation of ADI and ODI values for single units from V1. Circles indicate the ADI values for the right eye, triangles those for the left eye. (A) ADI/ODI distribution for cells with parafoveal RFs. (B) Distribution of ADI/ODI values for cells with peripheral RFs. Cells with parafoveal RFs show a systematic relationship between the ocular dominance index and the activity difference index. The stronger the input from the right eye on a given neuron, the stronger the activity differences under the two paradigms. Inset: values of the linear regression are given.

If cells with peripheral RFs are stimulated through the left eye, no activity differences were found at the population level [Fig. 5(C), ADI mean: 0.00 ± 0.15, $P > 0.05$). The spontaneous activity is slightly reduced during the control paradigm (ADI mean: -0.04 ± 0.16, $P > 0.05$). From the results presented in Fig. 5 it could be speculated, the more profound the influence from the right eye on the neuron, the more profound the activity difference under the two paradigms. For that reason we plotted the ocular dominance index (ODI) of each cell (see Methods) against the ADI (ODI values for cells dominated by the left eye will be positive, while those dominated by the right eye will be negative). A linear regression was applied to these data.

Cells with parafoveal RFs

The stronger the input from the right eye on a binocular V1 cell, the larger was the activity difference found. This was the case for cells stimulated through the right as well as the left eye [Fig. 6(A)]. The correlation coefficient of ODI and ADI values was slightly larger if cells were stimulated through the right eye (right eye $r = 0.54$ vs left eye $r = 0.48$).

Cells with peripheral RFs

The correlation coefficient was very small ($r < 0.1$) and the regression was flat [Fig. 6(B)]. These data show no striking correlation between the input strength of an eye on a neuron and the ADI values.

MT

Recorded neurons were taken to be within MT according to physiological criteria, i.e., to their characteristic direction selectivity, their RF size, and the topographic location of their RF in the contralateral visual hemifield.

The activity levels of four neurons from MT under the two conditions are shown in Fig. 4(D–G). Figures 4(D) and 4(E) show neurons that exhibited significantly higher activity if the neuron was stimulated through the *attentive eye*. Figure 4(F) displays an example where no significant differences were found, and in Fig. 4(G) a neuron with significantly higher activity during the switch-off paradigm is presented. From 34 neurons recorded, 11 showed significant differences during the control and switch-off paradigm. Eight of these 11 had elevated activity, and three had decreased activity if the cell was stimulated through the *attentive eye*.

As for V1, the results were separated according to the locations of the RFs, and according to the eye through which the cell was stimulated.

Cells with parafoveal RFs

Fourteen of thirty-four cells with parafoveal RFs were recorded in MT. Significant differences under the two

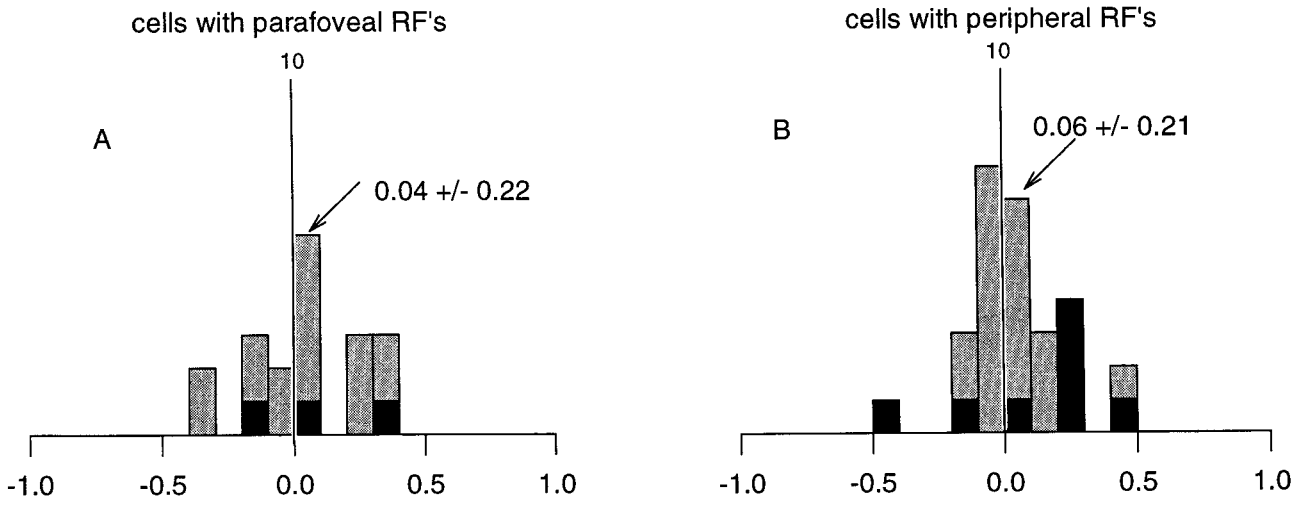

FIGURE 7. Distribution of ADI values for area MT. (A) Distribution of ADI values for neurons with RFs that included the parafovea. (B) Distribution for neurons with peripheral RFs. Black bars indicate incidences where significant differences were found under the two conditions. The population mean was positive for cells with parafoveal and peripheral RFs, indicating that activity was slightly higher when the cells were stimulated through the eye actively used for fixation (an ADI value of 0.06 corresponds to an activity difference of 12.7%, a value of 0.04 corresponds to an activity difference of 10.8%).

paradigms were found in three of these 14 cells. In two of them the activity was significantly higher if the cell was stimulated through the *attentive eye* [Fig. 7(A)]. One cell showed the opposite behaviour.

As in V1, the ADI population mean was higher when cells were stimulated through the right eye as compared to stimulation through the left eye. These differences, however, were not significant. Therefore, the respective values were treated as one group. The ADI population mean then was 0.04 ± 0.22 [Fig. 7(A), $P > 0.05$). The spontaneous activity population mean was 0.03 ± 0.23 ($P > 0.05$).

Cells with peripheral RFs

In 8/20 cells with peripheral RFs significant differences were found under the two paradigms. The activity was usually higher during the control paradigm [6/8, Fig. 7(B)]. In contrast to cells from V1, no major differences were found when cells were stimulated through the right or left eye (ADI population mean right eye: 0.06 ± 0.22; left eye: 0.05 ± 0.18). The spontaneous activity was slightly elevated during the control paradigm (right eye: 0.02 ± 0.27; left eye: 0.03 ± 0.22).

DISCUSSION

The behavioural and electrophysiological investigations in a macrostrabismic esotropic monkey gave no hint of deep amblyopia or any asymmetry at the single neuron level. Neurons from area V1 were predominantly binocular, which in strabismic animals only is the case if strabismus has occurred after the critical period (Hubel, 1979; von Noorden & Crawford, 1981; Wiesel, 1982; von Gruenau & Rauschecker, 1983; Kalil *et al.*, 1984). After late onset of strabismus, the monkey must, therefore, have lived under conditions comparable to permanent binocular rivalry (Blake, 1989). In areas V1 and MT we recorded neurons which significantly altered their response strength when they were stimulated through the fixating *attentive eye*, as compared to stimulation through the eye not used for fixation. In area V1 major differences were found for cells with parafoveal and peripheral RFs, if stimulated through the right eye. Cells with parafoveal RFs usually showed higher activity when they were stimulated through the *attentive eye*, as compared to stimulation through the eye currently not used for fixation. Cells with peripheral RFs on the other hand usually showed reduced activity when stimulated through the *attentive* right eye. When stimulated through the left eye, the ADI population mean was close to zero. In MT higher activity usually occurred when cells were stimulated through the *attentive eye*. The ADI population means for cells with parafoveal and peripheral RFs were similar.

The effects found here cannot be due to eye position effects, which were reported for neurons from MT, MST and parietal areas (Andersen *et al.*, 1990; Bremmer & Hoffmann, 1993) because the location of the eye in the orbit was nearly identical during the control and switch-off paradigms.

One might argue that the activity differences found for cells with parafoveal and peripheral RFs in area V1 and MT are due to different visual stimulation under the two conditions. In the control condition the eye sees a visual stimulus consisting of the target and an additional irrelevant visual pattern, while in the switch-off condition the target is absent (now fixated by the other eye). Removal of the foveal item should affect only cells with RF close to or including the fovea. This, however, is not the case. First of all, none of the neurons included in the present study responded to the fixation point itself. Second, in V1 and MT, significant differences were found for both cell types, those with either parafoveal or peripheral RFs. We doubt that stimulation outside the

classical RF is causing the effects described here. For parafoveal cells the target might be close enough to the RF to influence the response to the behaviorally irrelevant visual stimulus. A response enhancement under the control condition would be expected, if the target was suited to induce an increase of the RF of the recorded neuron, as reported for V1 neurons when specific surround stimulation was performed (Pettet & Gilbert, 1992). To our understanding this is highly improbable, since appropriate RF expansion was only found in these studies if the surround of the RF is stimulated about 10–15 min with sparing of the RF itself. After RF expansion, presentation of stimuli to the RF center causes the RF to shrink to its initial size immediately. In our study the target used is not very likely to cause RF expansion. Furthermore the target was present for only 2 sec, with an intertrial interval of about 1 sec. Finally, the stimulus moved twice within these 2 sec through the RF, enough to avoid RF expansion. It could still be argued that even without RF expansion, stimulation of the RF surround by the fixation spot could influence the response to the stimulus. A number of studies have addressed this issue (Nelson & Frost, 1978; Gulyas *et al.*, 1987; Gilbert & Wiesel, 1990). They all agree that stimulation of the RF surround more often has suppressive effects on the responses to the stimulus. Therefore, it is difficult to conclude that the increase of activity at the population level for cells with parafoveal RFs, as found in V1 and MT during stimulation of the attentive eye, should be due to the fixation target.

It could furthermore be argued that our results for parafoveal cells are due to interocular suppression. This would be a critical point, if interocular suppression was active with RF surround stimulation. Volchan & Gilbert (1992) have shown interocular transfer of RF expansion in cat visual cortex. This, however, has enhancing, not suppressive effects on the neuronal response. Interocular suppression has been found in normal (Sengpiel & Blakemore, 1994) and strabismic cats (Sengpiel *et al.*, 1994), if the receptive field of neurons is stimulated differently through the two eyes. In strabismic cats, stimulation of the non-dominant eye caused significant suppression only if the neuron was already responding to an appropriate stimulus in the dominant eye, but not when onset of stimulation in the two eyes was simultaneous. In normal cats, interocular suppression was only found if the two stimuli were of different orientations or phase and if the neuron was already responding to the preferred stimulus. Based on these specific temporal relationships required to induce interocular suppression, it is very unlikely that our findings can directly be compared to those described by Sengpiel *et al.* (1994). The cells in our study were never "already" responding to the stimulus when the fixation point was presented to the other eye.

Taken together, our experiments were able to demonstrate that, already in area V1, some mechanisms are established which enhance information coming from the foveating eye and attenuate information from the non-foveating eye. The same was true for cells recorded in area MT. In contrast to binocular rivalry experiments in normal monkeys, we find the majority of cells exhibit higher activity when stimulated through the *attentive eye*. Logothetis & Schall (1989) have performed binocular rivalry experiments in monkeys, and found equal numbers of MT cells with response enhancement (22%) and reduction (21%) during phases when the stimulus presented to the neuron was dominant. In a recent experiment, Leopold & Logothetis (1996) have investigated the neuronal response of V1, V2 and V4 neurons under conditions of binocular rivalry. The number of neurons that modulate their response to the stimulus was larger for V4 (Leopold & Logothetis, 1996) and MT (Logothetis & Schall, 1989) than for V1 and V2 neurons (Leopold & Logothetis, 1996). They report that the majority of neurons continue to respond to their preferred stimulus, even when it is perceptually suppressed. We do not know whether the stimulus in our paradigm is perceptually suppressed, but the neurons investigated also continue to respond to the stimulus, when the eye is not used for fixation. The number of neurons with significant modulation from MT in our study is slightly lower than reported by Logothetis & Schall (1989) (32% vs 43%). In V1, however, the proportion is higher (51% vs 18%, see Leopold & Logothetis, 1996).

Based on the psychophysical and neurophysiological results, we believe that the right eye is dominant. Accordingly, for V1 neurons the information coming from the fovea or parafovea of the right (dominant) eye is enhanced if the eye is used for fixation. Information coming from the periphery of this eye is suppressed if this eye is used for fixation. The information coming from the non-dominant left eye remains largely unaffected. In MT, however, the population activity was always higher when cells were stimulated through the fixating eye, independent of the eye used for fixation.

In conclusion, there are three major findings in the present study:

1. Neuronal activity of V1 cells with foveal and parafoveal RFs is enhanced, if elicited through the dominant right eye, whereas it is attenuated for cells with peripheral RFs when stimulated through the same eye. Conscious perception and object analysis is usually performed in the central visual field (and thus by cells with foveal and parafoveal RFs). If the dominant eye is the attentive eye, attention could support processing of foveal and parafoveal stimuli, and attenuate stimuli processed in the periphery of this eye. This is not necessarily restricted to a monkey with late onset of strabismus, but may well be the case in normal animals too.
2. The response reduction almost never resulted in a complete suppression of visual information. Information from retinal locations (and thus from the external world), which at a given moment has little significance, is suppressed only partially. Therefore, it is subconsciously processed, so that sudden changes in the external world can easily be detected.

These neuronal findings are consistent with psychophysical and electrophysiological findings during phases of binocular rivalry suppression (Fox & Check, 1968; Westendorf *et al.*, 1982; Logothetis & Schall, 1989; Leopold & Logothetis, 1996).

3. The normalized population activity was slightly higher ($\sim 10\%$) for parafoveal RFs when stimulated through the "attentive" eye. It is tempting to speculate that such small activity differences are sufficient to result in perceptual dominance.

Wiesenfelder & Blake (1990) propose that suppression of rivalrous targets takes place somewhere between V1 and MT. The suggestion is based on aftereffects that survive periods of rivalry (Blake & Fox, 1974; Lehmkuhle & Fox, 1975, Wade & Wenderoth, 1978; Wiesenfelder & Blake, 1991, 1992). This is consistent with the findings of Logothetis & Schall (1989), who report modulation but not suppression of cell responses in MT during phases of rivalry, and with our findings from area V1 and MT neurons. The finding that cells from area MT are modulated in our experimental conditions does not contradict the hypothesis, as this modulation could also have been induced in preceding areas. Still, congruent with Leopold & Logothetis (1996), we propose that suppression or attenuation of non-relevant information is a multi-stage process not completed in just one area, but organized according to the function and demands of each single area. Furthermore, suppression of rivalrous stimuli (and probably other stimuli as well) only attenuates the neuronal response to a level which does not reach consciousness, but guarantees that the respective stimuli are still represented at a neuronal level in the visual cortex.

REFERENCES

Aiello, A., Wright, K. W. & Borchert, M. (1994). Independence of optokinetic nystagmus asymmetry and binocularity in infantile esotropia. *Archives of Ophthalmology, 112*, 1580–1583.

Andersen, R. A., Bradwell, R. M., Gnadt, J. W. & Leonardi, F. (1990). Eye position effects of visual and saccade related activity in areas LIP and 7a of macaque monkey. *Journal of Neuroscience, 10*, 1176–1196.

Bedell, H. E., Yap, Y. L. & Flom, M. C. (1990). Fixational drift and nasal temporal pursuit asymmetries in strabismic amblyopes. *Investigative Ophthalmology and Visual Science, 31*, 986–996.

Blake, R. (1989). A neural theory of binocular rivalry. *Psychological Review, 96*, 145–167.

Blake, R. & Fox, R. (1974). Adaptation to invisible gratings and the site of binocular rivalry suppression. *Nature, 249*, 488–490.

Boothe, R. G., Dobson, V. & Teller, D. Y. (1985). Postnatal development of vision in human and non-human primates. *Annual Review of Neuroscience, 8*, 495–545.

Bremmer, F. & Hoffmann, K.-P. (1993). Pursuit related activity in macaque visual cortical areas MST and LIP is modulated by eye position. *Society of Neuroscience Abstracts, 19*, 1283.

Demer, J. L. & von Noorden, G. K. (1988). Optokinetic asymmetry in esotropia. *Journal of Pediatric Ophthalmology and Strabismus, 25*, 286–292.

Fox, R. & Check, R. (1968). Detection of motion during binocular rivalry suppression. *Journal of Experimental Psychology, 78*, 388–395.

Gilbert, C. D. (1993). Circuitry, architecture, and functional dynamics of visual cortex. *Cerebral Cortex, 3*, 373–386.

Gilbert, C. D. & Wiesel, T. N. (1990). The influence of contextual stimuli on the orientation selectivity of cells in primary visual cortex of the cat. *Vision Research, 30*, 1689–1701.

Gilbert, C. D. & Wiesel, T. N. (1992). Receptive field dynamics in adult primary visual cortex. *Nature, 356*, 150–152.

Gulyas, B., Orban, G. A., Duysens, J. & Maes, H. (1987). The suppressive influence of moving textured backgrounds on responses of cat striate cortex to moving bars. *Journal of Neurophysiology, 57*, 1767–1791.

Hoffmann, K.-P. & Schoppmann, A. (1984). Shortage of binocular cells in area 17 of visual cortex in cats with congenital strabismus. *Experimental Brain Research, 55*, 470–482.

Hubel, D. H. (1979). The visual cortex of normal and deprived monkeys. *American Scientist, 67*, 532–543.

Kalil, R. E., Spear, P. D. & Langtsemo, A. (1984). Response properties of striate cortex neurons in cats raised with divergent and convergent strabismus. *Journal of Neurophysiology, 52*, 514–536.

Kiorpes, L. (1989). The development of spatial resolution and contrast sensitivity in naturally strabismic monkeys. *Clinical Visual Science, 4*, 279–293.

Kiorpes, L. & Movshon, A. (1989). Differential development of two visual functions in primates. *Proceedings of the National Academy of Sciences USA, 86*, 8998–9001.

Kiper, D. C. & Kiorpes, L. (1994). Suprathreshold contrast sensitivity in experimentally strabismic monkeys. *Vision Research, 34*, 1575–1583.

Kommerell, G., Ullrich, D., Gilles, U. & Bach, M. (1995). Asymmetry of motion VEP in infantile strabismus and in central vestibular nystagmus. *Documenta Ophthalmologica, 89*, 373–381.

Lehmkuhle, S. W. & Fox, R. (1975). Effect of binocular rivalry suppression on the motion aftereffect. *Vision Research, 15*, 855–859.

Levelt, W. J. M. (1965). On binocular rivalry. Soesterberg, The Netherlands: Institut for Perception RVO-TNO.

Leopold D. A. & Logothetis N. K. (1996) Activity changes in early visual cortex reflect monkeys' percept during binocular rivalry. *Nature, 379*, 549–553.

Logothetis, N. K. & Schall, J. D. (1989). Neuronal correlates of subjective perception. *Science, 245*, 761–763.

Nelson, J. I. & Frost, B. J. (1978). Orientation selective inhibition from beyond the classic visual receptive field. *Brain Research, 139*, 359–365.

Pettet, M. W. & Gilbert, C. D. (1992). Dynamic changes in receptive field size in cat primary cortex. *Proceedings of the National Academy of Sciences USA, 89*, 8366–8370.

Schor, C. & Hallmark, W. (1978). Slow control of eye position in strabismic amblyopia. *Investigative Ophthalmology and Visual Science, 17*, 577–581.

Sengpiel, F. & Blakemore, C. (1994). Interocular control of neuronal responsiveness in cat visual cortex. *Nature, 368*, 847–850.

Sengpiel, F., Blakemore, C., Kind, P. C. & Harrad, R. (1994). Interocular suppression in the visual cortex of strabismic cats. *Journal of Neuroscience, 14*, 6855–6871.

Sireteanu, R. (1982a) Human amblyopia: consequence of chronic interocular suppression. *Human Neurobiology, 1*, 31–33.

Sireteanu, R. (1982b) Binocular vision in strabismic humans with alternating fixation. *Vision Research, 22*, 889–896.

Sireteanu, R. & Fronius, M. (1989). Different patterns of retinal correspondence in the central and peripheral visual field of strabismics. *Investigative Ophthalmology and Visual Science, 30*, 2023–2033.

Tychsen, L. & Lisberger, S. G. (1986). Maldevelopment of visual motion processing in humans who had strabismus with onset infancy. *Journal of Neuroscience, 6*, 2495–2508.

Volchan, E. & Gilbert, C. D. (1992). Interocular transfer of receptive field expansion in cat visual cortex. *Vision Research, 35*, 1–6.

von Gruenau, M. W. & Rauschecker, J. P. (1983). Natural strabismus in non-Siamese cats: lack of binocularity in the striate cortex. *Experimental Brain Research, 52*, 307–310.

von Noorden, G. K. & Crawford, M. L. J. (1981). Failure to preserve cortical binocularity in strabismic monkeys raised in a unidirectional

visual environment. *Investigative Ophthalmology and Visual Science, 20*, 665–670.

Wade, N. J. & Wenderoth, P. (1978). The influence of color and contrast rivalry on the magnitude of the tilt aftereffect. *Vision Research, 18*, 827–835.

Westendorf, D. H., Blake, R., Sloane, M. & Chambers, D. (1982). Binocular summation occurs during interocular suppression. *Journal of Experimental Psychology: Human Perception and Performance, 8*, 81–90.

Wiesel, T. N. (1982). Postnatal development of the visual cortex and the influence of the environment. *Nature, 299*, 583–592.

Wiesenfelder, H. & Blake, R. (1990). The neural site of binocular rivalry relative to the analysis of motion in the human visual system. *Journal of Neuroscience, 10*, 3880–3888.

Wiesenfelder, H. & Blake, R. (1991). Apparent motion can survive binocular rivalry suppression. *Vision Research, 31*, 1589–1599.

Wiesenfelder, H. & Blake, R. (1992). Binocular rivalry suppression disrupts recovery from motion adaptation. *Visual Neuroscience, 9*, 143–148.

Acknowledgements—The authors thank Dr Distler and Mrs M. Helmig for histological preparation. Supported by Deutsche Forschungsgemeinschaft HO450-19.