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Functional interactions between areas V1 and V2 in the monkey

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Summary — The role of feedback connections from area V2 to V1 was studied by reversible inactivation. When V2 was inactivated, the responses of some V1 neurons to stimulation of the surround region were increased while responses to center stimulation were unchanged or decreased. Latencies to small flashing stimuli were also compared in areas V1 and V2. The distributions in the two areas overlap largely, with a 10 ms shift between the two. Neurons of V1 and V2 that are driven by the magnocellular layers of the LGN are activated 20 ms earlier than neurons of the parvocellular stream.

receptive field / local connectivity / horizontal connectivity / feedback connectivity / visual cortex / V1 / V2 / center/surround

Introduction

Visual information coming from the retina is processed in a number of functional cortical areas, each containing a more or less complete representation of the contralateral visual hemifield. A dense network of corticocortical connections link together these areas and it is usual to distinguish two major set of connections, the feedforward and the feedback connections. Feedforward connections transfer information from areas located close to the point of entry of thalamic information in the cortex (area V1) to more distant higher order areas. Feedback connections send connections in the opposite direction. Feedforward connections are visuotopically organised, *ie* they link neurons representing the same region of the visual field. Feedback connections, on the contrary, are not visuotopically organised. Hence, neurons in lower order areas receive feedback information from cortical regions encoding a larger part of the visual field than their receptive fields (Salin and Bullier, 1995). In addition, feedforward and feedback connections possess different morphological characteristics, especially concerning the laminar distributions of their parent neurons and of their terminal arborizations (Felleman and Van Essen, 1991; Salin and Bullier, 1995).

Methods and aims

Despite the extensive anatomical knowledge concerning corticocortical connections in the visual system, relatively little work has been done to test their functional role. It has been demonstrated that feedforward connections constitute the major source of neural drive from V1 to areas of the ventral occipito-temporal stream, but that additional subcortical inputs are present in areas of the dorsal occipito-parietal stream (Bullier *et al*, 1994). Much less is known concerning the role of feedback connections. We have studied the feedback connections between areas V2 and V1, using methods of reversible inactivation of cortical tissue.

Another matter has attracted our interest recently, that of the temporal aspect of cortical processing. Corticocortical connections are usually slow (a few m/s), due to the small calibre of their axons. Because of the slow transfer of spikes by cortical axons and the long integration times of cortical neurons (of the order of 10 ms; Nowak and Bullier, 1996), there must be substantial delays in the activation of successive cortical areas when they are organised in serial fashion, as is the case for V1 and V2. These delays represent a potential limitation of the role of feedback connections, since the risk is important that feedback messages get back to lower order areas too late to modify the wave of afferent activity coming from the retina. This is particularly crucial for inhibitory influences that require an extra synaptic step through inhibitory interneurons since most corticocortical connections are made by excitatory neurons (Salin and Bullier, 1995). To understand the timing of information transfer between areas V1 and V2 we measured the latencies of neurons to visual stimulation in these two areas.

A study of feedback connections

We tested the role of feedback connections between areas V2 and V1 by recording single units in area V1 while inactivating a retinotopically corresponding region in V2 by small volumes of 100 mM GABA ejected from a set of three micropipettes arranged in a triangle with 1 mm of separation. Experiments were performed on cynomolgus monkeys paralysed and anaesthetised with nitrous oxide and suffenta. We measured the effects of such inactivation on the responses of V1 neurons to a set of flashing stimuli designed to activate the receptive field centre (the activating region of the receptive field, also called the classical receptive field (CRF)) and various combinations of centre and modulatory surround.

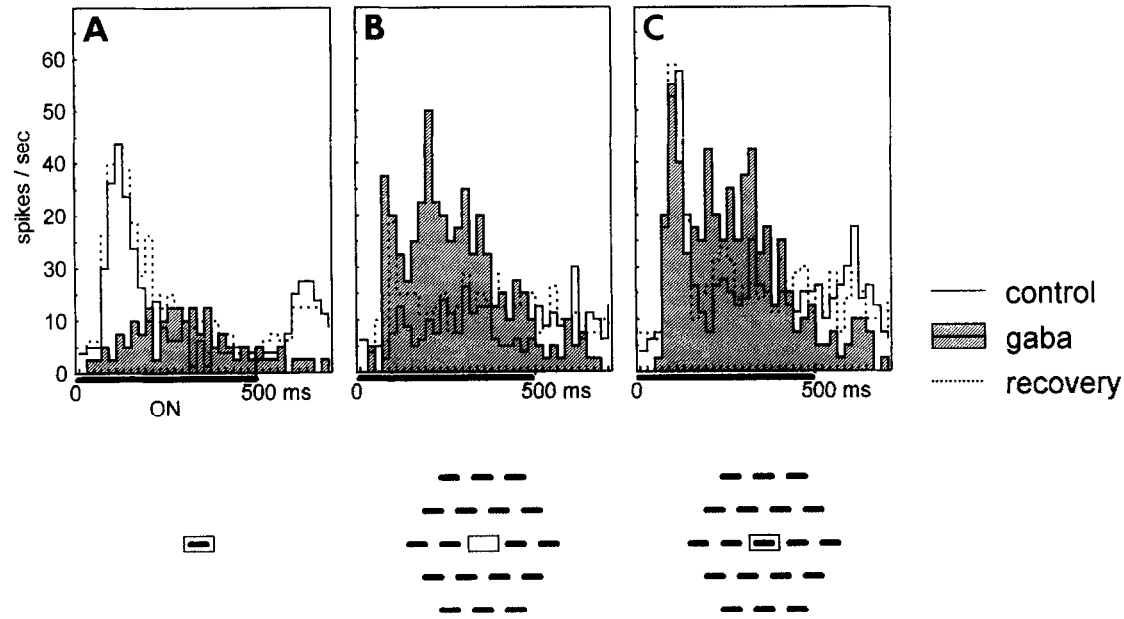

Fig 1. Effect of GABA inactivation of area V2 on the responses of a neuron recorded in the retinotopically corresponding region in V1. Three sets of post stimulus histograms (PSTHs) are shown. In each set, the responses are shown for a control run, a GABA run and a post-GABA recovery run. The left set of PSTHs corresponds to the responses of the neuron to stimulation in the receptive field centre (illustrated by the small rectangle below the PSTHs). The central set of PSTHs illustrates the responses to stimulation in the receptive field modulatory surround. Note the strong amplification of the response during GABA inactivation of V2. The right set of PSTHs illustrates the responses of the neuron to stimulation of centre and surround. Here also, V2 inactivation potentiates strongly the response. Neuron FAK.e1; bin width 20 ms.

In some neurons, inactivation of V2 had no effect on the response of neurons in V1. In other neurons, we observed effects similar to those presented in figure 1. The left set of PSTHs illustrates the response of a single unit in V1 to a small bar of optimal orientation flashed in the receptive field centre (represented by the rectangle surrounding the stimulus). GABA inactivation of the retinotopically corresponding region of V2 led to a substantial decrease of the early part of the ON response and a disappearance of the OFF response.

When the stimulus was activating the modulatory surround of the receptive field (centre set of PSTHs), the effect of GABA inactivation of V2 was opposite to that observed in the centre. The surround ON response was substantially increased by the V2 inactivation. In fact, during V2 inactivation the response to stimulation of the modulatory surround was much stronger than that given by stimulating the receptive field centre. Finally, when centre and surround stimuli were combined (right set of PSTHs), the inactivation of V2 led to a strengthening of the sustained part of the ON response and a disappearance of the OFF response. During the recovery runs, after neural activity had returned in V2, the responses came back to their original levels. It is clear that the selectivity of the neuron was completely changed by inactivation of feedback connections from V2. Before inactivation the neuron responded best to a stimulus that included the receptive field centre. When the feedback from V2 was abolished, the strongest response was obtained when the stimulus included the receptive field surround.

The most frequent effect that we observed in V1 neurons during V2 inactivation was an increase in the response to stimulation in the surround. This was sometimes, but not always, accompanied by a decrease of the response to centre stimulation as shown in figure 1. In neurons which showed an increase in surround responses, the responses to combined centre and surround stimuli were increased. The result was a reversal of the spatial selectivity of these receptive fields. With the V2 feedback active, responses were often strongest to small stimuli. Without feedback from V2, the strongest responses were obtained by a much larger stimulus covering centre and surround. Thus, feedback connections can modify the receptive field selectivity of neurons in lower order areas.

These results suggest that the feedback connections from V2 to V1 act *via* a push-pull mechanism, activating the centre mechanism and inhibiting the surround. This usually leads to an increase in the quantity of information transmitted by the feedforward connections, a conclusion similar to that reached by McClurkin and collaborators concerning the role of the corticothalamic connections (McClurkin *et al*, 1994). If we assume that most of our recordings in V1 are from pyramidal neurons, we can make some predictions concerning the feedback connectivity from V2 to V1. Our results suggest that neurons in V2 send precise excitatory connections to pyramidal cells in V1 with overlapping receptive field centres and more diffuse excitatory connections to non-pyramidal inhibitory cells with neighbouring receptive fields. Since neurons of the supragranular layers in V2 have smaller receptive fields and less diverging connections than neurons of the infragranular layers (Barone *et al*, 1995), it is likely that they provide the precise excitatory input whereas neurons of the infragranular layers generate the diffuse inhibitory halo. Consideration of timing issues (see below) are also in keeping with such a hypothesis.

Temporal aspects of cortical processing in areas V1 and V2

All neurons in V2 are silenced when V1 is inactivated (Girard and Bullier, 1989). Since V1 is the main recipient of geniculate input in primates (Bullier *et al*, 1994), V2 neurons are likely to be activated later than neurons in V1. One would expect therefore that inactivation of V2 concerns only the later part of the response to visual stimuli. However, we observed many cases in which inactivation of V2 led to a change in the early portion of the response, as illustrated in figure 1. This suggests that latencies of some V2 neurons are very short and that latencies to visual stimulation of interconnected neurons in areas V1 and V2 are well matched.

In order to characterise more precisely the timing of activation of neurons in areas V1 and V2 to visual stimulation we recorded the response latencies of neurons in these areas to stimulation with small flashing bars of optimal orientation placed in their receptive field centres (Munk *et al*, 1995; Nowak *et al*, 1995). Recordings were made from more than 200 sites in each area and approximately half the sample was obtained during paired recordings in areas V1 and V2. On average, the latencies of V2 neurons lag by about 10 ms behind those of neurons in V1 (Nowak *et al*, 1995). A 10-ms delay corresponds to the sum of the average axon conduction delay between these areas and the mean integration time of neurons in V2 (Nowak and Bullier, 1996). This suggests that information is passed on to V2 as soon as it arrives in V1. There is a substantial range of values (60–150 ms after stimulus ON or OFF) for which the latencies in the two areas overlap. During that extended period, processing is done simultaneously by neurons in the two areas. Therefore, one can conclude that the two areas do not work in a strictly serial fashion, with V1 processing information before transferring it to V2 (Bullier and Nowak, 1995).

The earliest latencies in V1 are observed in layers 4Cα and 4B, which relay the information from the magnocellular layers of the LGN. Such an early activation is consistent with the results of Marrocco who showed that the LGN neurons that respond transiently to flashes and are concentrated in the magnocellular layers have shorter latencies than neurons with sustained responses which tend to be concentrated in the parvocellular layers (Marrocco, 1976). The similarity in latency difference between transient and sustained cells in the LGN (20 ms) and between neurons in layers 4Cα and 4Cβ in V1 suggests that the cortical results are due to latency differences in LGN neurons that probably originate in the retina (Nowak and Bullier, 1996).

Latency differences between M and P streams were also observed in area V2. Neurons of the thick cytochrome oxidase bands have shorter latencies than those of neurons in the thin cytochrome oxidase bands. It is known that the thick bands receive their V1 input from layer 4B and thus belong to the M stream. Neurons in the thin bands, on the other hand, are innervated by cells in cytochrome oxidase blobs in V1 that receive converging inputs from the M and P pathways (Lachica *et al*, 1992). The latency difference between thin and thick cytochrome oxidase bands in V2 (20 ms) is similar to that observed between layers 4Cα and 4Cβ in area V1 and, again, may simply reflect the difference between latencies of P and M neurons in the LGN.

The earliest latencies in area V2 were recorded in the infragranular layers. They were not significantly different from those of infragranular layers in V1 and were 10 ms shorter than the latencies of supragranular layers of V1 (Nowak *et al*, 1995). This observation is in keeping with a possible role of V2 infragranular layers in providing a rapid input to inhibitory neurons in V1 that produce a diffuse inhibitory action on V1 pyramidal cells, as suggested above.

Conclusion

Latency measurements in areas V1 and V2 do not simply reflect the sequential order of processing expected

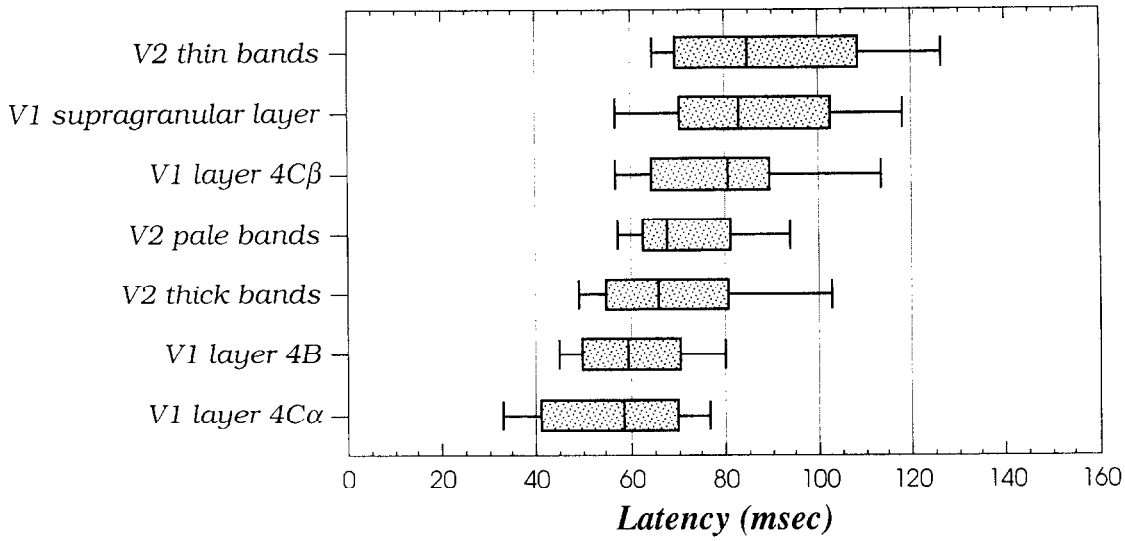

Fig 2. Distributions of latencies to visual stimulation in different modules of areas V1 and V2 of the macaque monkey. The central box corresponds to the 25–75% centile (vertical line is the median). The small vertical bars on either side of the box correspond to the 10 and 90% centiles. Thin, thick and pale bands refer to the cytochrome oxidase bands in area V2. Redrawn from Bullier and Nowak (1995).

from a purely serial organisation. This is illustrated in figure 2 that presents the distributions of latencies in different anatomical modules in the two areas. It appears that, in area V2 as well as in V1, much of the early processing occurs in a fast pathway dominated by the M input (layers 4Cα and 4B in V1, thick bands in V2). The latency study also reveals that many V2 neurons, particularly in the infragranular layers and in the thick cytochrome oxidase bands, are activated sufficiently rapidly by their M input to play a role in shaping the early part of the responses of P-dominated neurons in V1 that are activated later by the visual stimuli.

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