

Role of the Motor Cortex in the Initiation of Voluntary Motor Responses in the Cat

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We have previously shown that cats can be trained to make rapid and accurate tracking responses with their forelimbs in relation to a target which is suddenly displaced (Ghez and Vicario 1978a,b; Ghez 1979). Behavioural studies revealed that in the cat such motor responses are typically made with the extraordinarily short latency of 50–70 msec. Since these latencies are not affected by conditions of behavioural choice (Ghez and Vicario 1978a; Ghez 1979) we have hypothesized that neural presetting mechanisms enabled prior to the stimulus might play an important role in the sensorimotor transformation required in this tracking task. In the present study we have recorded the activity of neurones in the motor cortex of the behaving cat to determine their role in rapid reaction time responses. The questions we wished to address were: first, can the motor cortex contribute to the initiation of responses with such short reaction times? Second, do the patterns of activity of task-related neurones provide some insight into the nature of presetting mechanisms occurring prior to response initiation? Third, what relation exists between task-related neural activity and the receptive fields of neurones in the motor cortex? Abstracts of these results have been published (Vicario et al. 1980; Martin et al. 1981).

METHODS

The activity of single neurones in the motor cortex was recorded in cats trained to apply force with the forearm on a stationary lever so as to match a criterion target level. The animals were provided with a display of their force error consisting of a feeding device which was moved to the right or the left of their midline by means of a servo-controlled torque motor. Flexor or extensor adjustments in force applied to the lever by the animals were elicited by stepping the criterion target level in one or another direction after a random interval of initial alignment. This produced a shift to the right or the left in the position of the display to which the animals had to respond by making an appropriate compensatory change in the force applied to the lever. Movement of the display could be detected visually by the animals or through mechanical deflection of their vibrissae.

In a first series of experiments, animals were trained to make extensor responses to changes in target level shifting the display to the right and to make flexor respon-

ses to display shifts to the left. In a second series of experiments, a more complex paradigm was utilized. To dissociate the coding of direction and magnitude of display movement (i.e. stimulus) from that of response variables in task-related unit activity, animals were trained to respond appropriately when the polarity of displayed error was inverted, or its gain altered. Thus, a response of a given magnitude and direction could be elicited by display movements in either direction and of various sizes. Additionally, the effects of display shifts not eliciting responses were examined. In this last condition reward was withheld and unitary activity was examined following behavioural extinction (extinction trials). Peripheral receptive fields of single units and the effects of intracortical microstimulation (ICMS) from the recording sites were routinely checked. Stimuli consisted of 45 msec trains of biphasic pulses (0.02 msec per phase) at 300 Hz. Projection neurones were identified antidromically from electrodes chronically implanted in the cerebral peduncles in sites where stimulation elicited contraction of contralateral forelimb muscles at low threshold.

RESULTS

(1) Area sampled: regional differences in receptive fields and in timing of task-related activity

Penetrations were made in the lateral portions of the anterior and posterior sigmoid gyri. ICMS was applied at 500 μ m intervals to ascertain the position of the electrode tip within the overall somatotopic representation in the motor cortex. Single neurones were sampled in areas where ICMS produced contraction of forelimb muscles with a threshold of 20 μ A or less. Approximately 450 neurones examined showed clear temporal relations between their changes in activity and behavioural events associated with task performance. Most neurones could also be driven by peripheral stimuli applied to different body parts while the animal was at rest and not performing the tracking task.

Regional differences in receptive field characteristics and in the timing of unit activity were observed. Throughout the arm area of the motor cortex (defined by ICMS) neurones were found with clear and discrete receptive fields (simple fields) of the type described by previous authors (Welt et al. 1967; Asanuma 1975). In addition, neurones were observed with more complex receptive field characteristics (complex fields). The response of some of these neurones to peripheral stimuli was temporally labile, being brisk at times and diminishing or disappearing entirely within seconds or minutes, only to reappear a short time later (cf. also Welt et al. 1967). Other complex field cells could only be driven by moving cutaneous stimuli in a single direction while still others showed excitatory or inhibitory regions within their receptive fields, or discontinuous excitatory foci suggesting complex patterns of convergence. Taken as a group, neurones with these complex properties were preferentially located in rostral regions of area 4 γ , anterior to the cruciate sulcus. While task-related neuronal activity was observed in both caudal and rostral sites, it

was only in rostral regions that units were found which, on average, modulated their activity in advance of the animals' force response (lead cells). Although lead cells constituted only about 10% of the task-related units, they were subjected to more extensive evaluation because only this population could have contributed to response initiation.

Approximately 80% of lead cells had receptive fields of the complex type suggesting that lead cells receive complex convergent patterns of peripheral input. 90% of lead cells showed reciprocal response patterns characterized by increased activity with forces developed in either the flexor or extensor direction and decreased or no modulation with force developed in the opposite direction. The modulation in unit activity of these lead cells could be characterized as either phasic (14%), tonic (22%) or, in the majority of cases (64%) as mixed. In 80% of neurones the degree of modulation varied with either the rate of change of force, the steady force developed or the integrated electromyographic activity (EMG) in the agonist muscle. In neurones whose activity was modulated following the onset of force production, the change could generally be attributed to stimulation of the neurones' receptive fields which accompanied the behavioural response. For example, neurones which could be passively driven by cutaneous stimuli applied to the hair on the dorsal surface of the forearm were typically phasically active with flexor responses of the forearm.

(2) Timing of lead cell activity: stimulus synchronization

A surprising observation was that the onset of changes in unit activity of lead cells was better related in time to the occurrence of the stimulus (i.e., the display shift consequent on the target step) than to the onset of the response (operationally defined as the first change in dF/dt). This observation is illustrated in Fig. 1, which shows rasters of unit activity synchronized with the onset of force production (time zero on abscissa) sorted in order of progressively increasing reaction time. The shortest reaction times are at the top of the rasters and the longest at the bottom. The small plus signs mark the time of occurrence of the stimulus eliciting the response. Part A represents unit activity associated with a series of extensor responses elicited by display movement to the right. Part B shows activity with flexor responses following display movement to the left. Inspection of these rasters clearly shows that both increases (A) and decreases (B) in density of unit activity have a slope that parallels the stimulus mark rather than remaining aligned with the onset of the response (time zero). Fig. 1C and D illustrate the relationship between the amount of lead of increases (C) and decreases (D) in unit activity expressed as a function of reaction time. Units such as this, whose timing was better related to the occurrence of the stimulus than to that of the response, showed significant correlation coefficients and positive slopes of the lead time-reaction time regression line. Units bearing a constant lead over the onset of motor responses would be expected to exhibit a slope of zero. No units with this property were observed in our sample of lead cells. Neurones discharging after the onset of the response (lag cells) showed lead-reaction time regression slopes which were close to zero or correlation coefficients which were not

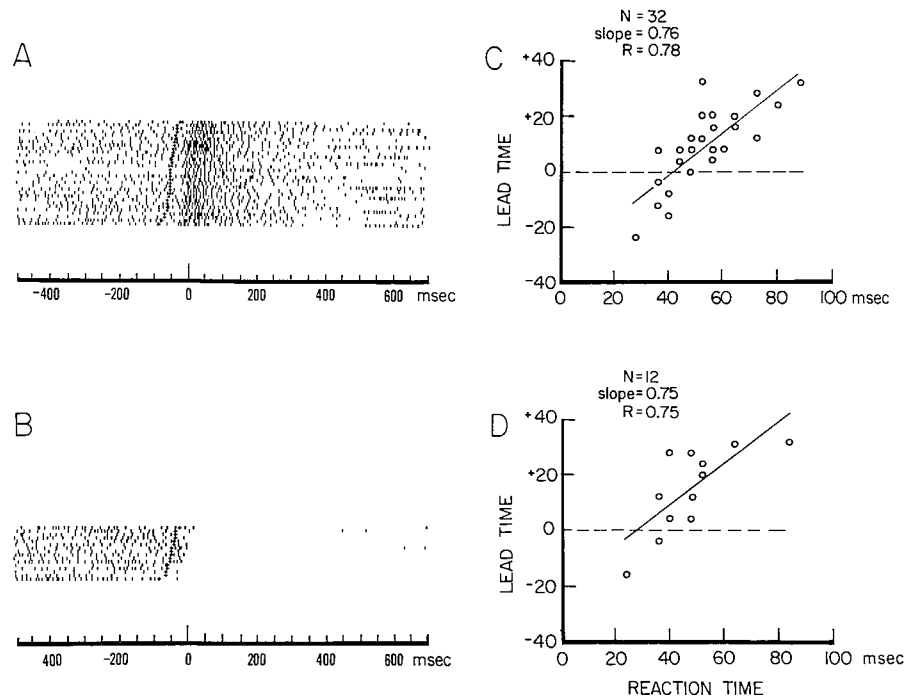


Fig. 1. Raster displays of spike activity associated with extension (A) and flexion (B). Trials are sorted and displayed from top to bottom in order of progressively increasing reaction time (RT). + signs indicate time of occurrence of shift in display position. C and D: scatter plots for lead time (time from change in unit activity to change in force exerted) as a function of reaction time (time from shift in display to onset of force change) for rasters on left.

significant. In these cases the lag was of approximately constant duration, an observation which is compatible with these cells being driven by activation of their receptive fields in the course of the behavioural response.

(3) Behavioural contingencies determining lead cell activity

The activity of lead cells was contingent on the occurrence of behavioural responses. When reinforcement was withheld and behavioural responses extinguished, changes in unit activity no longer followed shifts in the display. Additionally, peri-response time histograms of unit activity in trials where the responses were spontaneously aborted (or undershot) showed intermediate amounts of modulation. These observations suggest that target-related sensory information is conveyed to neurones in the rostral portion of the arm area of motor cortex in a contingent fashion. Two possible mechanisms may be envisaged. First, the behavioural set associated with task performance uncovered a latent receptive field in a fixed location which escaped observation when the animal was examined under passive conditions. Alternatively, the stimulus site producing excitation or inhibition in a given neurone could vary according to the direction of response required by the stimulus.

To distinguish between these possibilities we recorded the patterns of activity of

lead cells in rostral motor cortex in animals trained to respond appropriately when the polarity of displayed error was inverted. With this paradigm it was possible to examine neuronal activity associated with flexor and extensor responses elicited by movements of the display to both the right and the left. Two classes of lead cells, with approximately equal numbers, were observed in rostral motor cortex. The first class showed reciprocal changes in activity (i.e. increases or decreases) contingent on the direction of force production and independent of the direction of display movement. The timing of the onset of changes of activity was, however, more consistently related to the onset of target shift than to the onset of force production. These observations suggest that display-related afferent input reaching neurones in rostral motor cortex can be selected according to behavioural set, possibly by gating mechanisms acting on neurones presynaptic to them.

In the second class of lead cells, activity was contingent on a single direction of display movement and the pattern of activity did not vary with the direction of force production by forelimb muscles. Modulation in activity of these cells while timed to the stimulus was contingent on the occurrence of the motor response. This class of cells could be important in the processing of stimulus information, leading to the development of a motor command. Alternatively, such cells might control one or more independent behavioural responses which we have observed in our behavioural paradigm. Such responses included attempts at head rotation and eye movement towards the moving display, the direction of which was independent of the polarity of displayed error and of the direction of force produced by forelimb muscles.

CONCLUSIONS

(1) The present findings suggest that the arm area of the cat motor cortex includes 2 functionally distinct regions: one rostral, the other caudal to the cruciate sulcus. For convenience, these 2 regions may be denoted as MCr and MCc. Our findings complement the earlier experiments of Pappas and Strick (1979) using microstimulation. Parallel anatomical studies using retrograde and anterograde transport of HRP and/or radiolabelled amino acids (Yumiya and Ghez 1981) have revealed differential cortico-cortical and thalamo-cortical projections to these 2 regions. Since the modulation of unit activity in MCc invariably lagged the onset of behavioural responses, this region cannot be considered to play a role in response initiation. Only in MCr were neurones encountered whose activity, on average, was modulated in advance of overt behaviour. While neurones in MCr could play a role in the initiation of behavioural responses, the small number of cells with this property emphasizes the importance of subcortical and other parallel pathways in mediating behaviour.

(2) A surprising observation was that the onset of lead activity was better correlated in time with the target stimulus than with the motor response. Since neuronal activity was dependent on the occurrence of the motor behaviour, the results suggest that target information may be relayed to neurones in MCr in a contingent fashion.

These observations support the notion that gating mechanisms acting presynaptically to neurones in MCr enable the efficient transfer of target information leading to motor commands. These findings suggest that similar conclusions drawn by Evarts and Tanji (1974) in relation to proprioceptive inputs may have more general implications. Thus, in the context of a task requiring spatially accurate responses to stimuli moving in one or another direction, gating mechanisms implement, within the motor cortex, a preset map that relates target and response dimensions. While aggregate lead activity in MCr could represent a command that determines both response configuration and its time of onset, it cannot be excluded that its action is also in the nature of a gating signal applied to a lower order station. Since lead activity in MCr is better timed to the occurrence of the target stimulus than to that of the response, the variance in reaction time must be strongly influenced by other mechanisms. Thus, reaction time variance may represent an emergent property resulting from the activity of multiple descending and afferent pathways acting on intercalated interneurons and motor neurones.

(3) Since both lead and lag cells often showed peripheral receptive fields in the responding limb and since sensory inputs reaching these neurones may be subject to gating mechanisms, it cannot be excluded that somatosensory inputs contribute to observed parametric relations between unit activity and force exerted.

(4) The present results suggest that the classical dichotomies drawn between sensory and motor mechanisms and between activity within the central nervous system which leads or lags behaviour may not be as useful as once thought. Consideration of the nature of information processing required in a particular task may provide a more fruitful point of departure in elucidating the neural translation between sensory events and motor responses.

REFERENCES

- Asanuma, H. Recent developments in the study of the columnar arrangement of neurons within the motor cortex. *Physiol. Rev.*, 1975, 55: 143–156.
- Evarts, E.V. and Tanji, J. Gating of motor cortex reflexes by prior instruction. *Brain Res.*, 1974, 71: 479–494.
- Ghez, C. Contributions of central programs to rapid limb movement in the cat. In: H. Asanuma and V.J. Wilson (Eds.), *Integration in the Nervous System*. Igaku-Shoin, Tokyo, 1979: 305–320.
- Ghez, C. and Vicario, D. The control of rapid limb movement in the cat. I. Response latency. *Exp. Brain Res.*, 1978a, 33: 173–190.
- Ghez, C. and Vicario, D. The control of rapid limb movement in the cat. II. Scaling of isometric force adjustments. *Exp. Brain Res.*, 1978b, 33: 191–203.
- Martin, J., Yumiya, H. and Ghez, C. Coding of target and response variables in cat motor cortex. *Neurosci. Abstr.*, 1981, 7: 562.
- Pappas, C.L. and Strick, P.L. Double representation of the distal forelimb in cat motor cortex. *Brain Res.*, 1979, 167: 412–416.
- Vicario, D., Martin, J. and Ghez, C. Discharge of neurons in cat motor cortex during voluntary muscle contraction. *Neurosci. Abstr.*, 1980, 6: 125.
- Welt, C., Aschoff, J.C., Kameda, K. and Brooks, V.B. Intracortical organization of cat's motorsensory neurons. In: M.D. Yahr and D.P. Purpura (Eds.), *Neurophysiological Basis of Normal and Abnormal Motor Activities*. Raven Press, New York, 1967: 255–293.
- Yumiya, H. and Ghez, C. Topography of differential projections to rostral and caudal cat motor cortex. *Soc. Neurosci. Abstr.*, 1981, 7: 562.