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INPUT FROM MUSCLE AND CUTANEOUS NERVES OF THE HAND AND FOREARM TO NEURONES OF THE PRECENTRAL GYRUS OF BABOONS AND MONKEYS

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SUMMARY

1. The precentral bank of the Rolandic fissure of the cortical arm area has been explored with extracellular micro-electrodes in primates (baboons and monkeys) under nitrous oxide and oxygen anaesthesia, supplemented by small doses of Parkesernyl® and chloralose. The results in baboons and monkeys were the same.

2. Single units were classified as pyramidal tract neurones or non-pyramidal tract neurones according to their antidromic responsiveness to stimuli applied in the dorsolateral funiculus at C1–2.

3. Responses to electrical stimulation of the deep (motor) radial nerve, the deep palmar (motor) branch of the ulnar nerve, and the superficial (cutaneous) radial nerve could be recorded in the majority of neurones of the motor cortex provided that short trains of strong stimuli were used. Minimal responses to muscle nerve stimulation were observed in a few neurones at 1·4 × group I threshold, but most units reacted only with higher stimulus intensities (2–3 × group I threshold).

4. The latencies to peripheral nerve stimulation were measured from the first peak of the incoming volley recorded at the root entry zone. The mean response latencies of pyramidal tract cells were between 20 and 25 msec; non-pyramidal tract cells were activated at slightly shorter mean latencies, the difference being significant for superficial radial nerve stimulation only (4 msec). These latencies are more than twice as long as those recorded in the postcentral gyrus, and the probability of discharge is lower than for postcentral neurones.

5. A further difference between neurones of the postcentral and precentral gyrus is the pronounced convergence from different nerves and also from different modalities (cutaneous and muscle afferents) in units of the precentral cortex in contrast to units of the postcentral cortex.

6. The high thresholds, necessary to activate precentral neurones by muscle nerve stimulation, make it unlikely that group I muscle afferents are involved. This is, furthermore, indicated by the lack of responsiveness to intravenous injection of succinylcholine which was, however, effective for driving neurones of the specific projection area for group I afferents, area 3a. The present experiments are consistent with the view that sensitivity of precentral neurones to muscle stretch (described in previous studies) is due to activation of secondary muscle spindle endings and their ascending pathways.

7. The original hypothesis of a load compensating 'pyramidal reflex' with an oligosynaptic afferent contribution from the spindle primaries can be discarded. The present findings indicate that there is a feed-back from secondary muscle spindle afferents which, by way of a more complex pathway, can modulate the firing frequency of neurones in the motor cortex.

INTRODUCTION

This paper continues research on proprioceptive effects at the cortical level. The analysis is devoted to the hand of primates and its cortical representation. The starting point was the observation of Evarts (1967) that pyramidal tract (PT) cell discharges, correlated with a standardized displacement of the arm, were most intensive if the displacement had to be exerted against load. In a previous study (Phillips, Powell & Wiesendanger, 1971), the hypothesis of a transcortical servoloop for the control of PT cell firing by way of primary muscle spindle endings was investigated. Such a hypothesis of a load compensating 'pyramidal reflex' seemed promising, since the hand muscles in primates are richly supplied with muscle spindles; moreover, the gain of the segmental stretch reflex pathway is rather low (Matthews, 1972) and one may thus assume that the muscle spindle afferents exert some control of skilled hand movements at higher levels of the neuraxis.

It was found that impulses from the primary muscle spindle endings reach a subdivision of the somatosensory cortex, area 3a, which lies at the bottom of the Rolandic fissure (Phillips *et al.* 1971). However, evoked responses to low intensity muscle nerve stimulation were not recorded in the motor cortex, although some responses were seen with stronger stimuli.

The present experiments were designed to study the timing of the muscle afferent input to the motor cortex and to measure the threshold of the primary afferents involved. A cutaneous nerve was also stimulated for comparison. It was found that electrical stimuli exceeding group II thresholds must be applied to muscle nerves in order to excite precentral neurones. In contrast to responses of neurones of area 3a, the responses of

the precentral neurones were less tightly coupled and there was a remarkable convergence from different nerves and different modalities. The exact pathway for these contributions has yet to be defined.

Preliminary results were communicated at a recent symposium on 'Neural Control of Motor Performance' and were published as a short communication (Wiesendanger, 1972).

METHODS

Seventeen baboons (3·8–7·7 kg) and four monkeys (2·1–2·8 kg) were used in these experiments. Only a few neurones of the precentral cortex were investigated in the first eleven experiments which were primarily devoted to the study of area 3a (Phillips *et al.* 1971). These animals were anaesthetized with 50–70 % N_2O in O_2 with supplementary small doses of pentobarbitone in order to prevent movements. Later experiments were designed to study the effects of afferent input to neurones of the precentral cortex. Experience showed that barbiturates greatly depressed the sensitivity of precentral neurones to afferent nerve volleys. Most of the results here presented were obtained from six baboons and four monkeys under 50 % N_2O anaesthesia, supplemented by repeated small doses of Parkesernyl® (1 mg/kg I.M.) or chloralose (10 mg/kg I.V.). The procedure for preparing the deep (motor) radial nerve, superficial (cutaneous) radial nerve, and of the deep motor branch of the ulnar nerve in the palm (= 'deep ulnar nerve') as well as exposure of the peri-Rolandic cortex and of the cervical spinal cord (C1–T2) is the same as that described in a previous paper (Phillips *et al.* 1971).

Micro-electrodes (tungsten or capillaries filled with 4 M-NaCl) were driven perpendicularly to the cortical surface into the precentral gyrus by means of an eletronically controlled stepping micro-manipulator (Transvertex, Sweden). Exact localization of recording sites was not as crucial in these experiments as in those of area 3a. All recordings were made within the lowest threshold focus (S+, 5 msec pulses, < 1·5 mA) for flick movements of the thumb (Fig. 1*A*). The majority of units were identified as pyramidal tract units (PT units) by antidromic invasion according to the well known criteria (Patton & Amassian, 1960). The corticospinal axons were excited by means of two fine needle electrodes insulated except at the tips and placed within the dorsal half of the lateral funiculus at C_2. Some non-PT units, all of them recorded nearby identified PT-units, were also included in this study. Typically, the electrode was inserted as close as possible to the vessels of the central fissure and passed more or less tangentially to the layers of area 4 of the buried cortex as verified in several experiments by cutting the brain along an implanted tungsten electrode at the end of an experiment (see Fig. 1*B*). The depth of the recording site was read from the micro-manipulator. Since units were recorded all along the buried cortex down to a depth of about 8 mm from the surface, the depth recordings cannot be strictly related to the different cortical layers.

The incoming volley was monitored triphasically by means of a silver ball electrode placed at the dorsal root entry zone. Since the best recording points for the radial nerve volley was more rostral than for the ulnar nerve volley, a current intensity-amplitude plot was effected at the best respective points at the root entry zone prior to recordings of the cortical cells. In searching for cortical units, the motor nerves were stimulated well above threshold for a motor twitch (about 2–3 × threshold for the group I volley). When a cell was isolated, the responses were recorded first at this intensity; then the intensity was gradually reduced in order to have an estimate of the threshold intensity. Since, by inspection it was in most

cases difficult to decide whether the spike discharges were spontaneous or in response to these low intensity stimulations, poststimulus time histograms were constructed either by plotting the spike discharges from 15–20 sweeps recorded on films or by means of on-line computing with a CAT 400 B.

In four experiments (three baboons and one monkey), the responsiveness to succinylcholine of precentral and 3a neurones was compared; the drug, known to excite preferentially primary spindle endings and much less secondary spindle endings (Fehr, 1965), was administered I.V. at doses of 0·5 mg/kg. Dot displays of

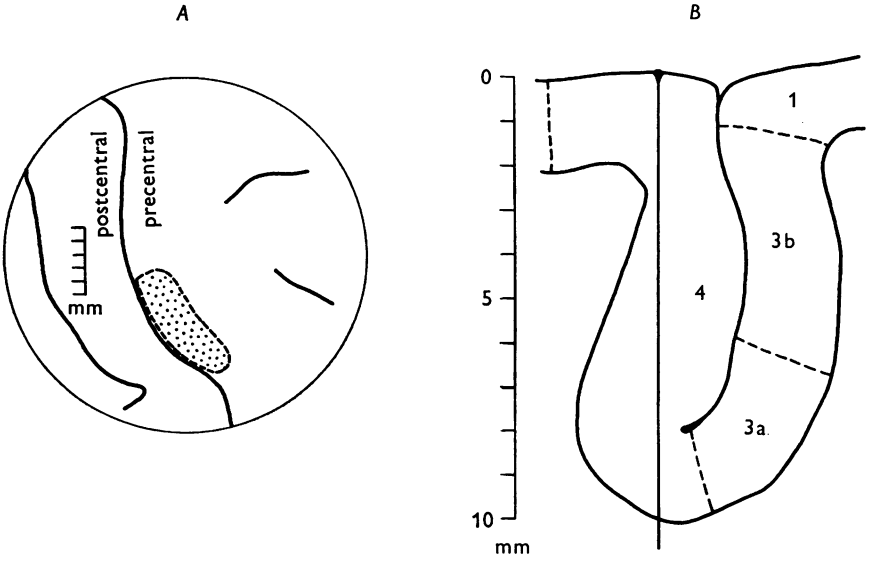

Fig. 1. *A*, area of exposed cortex (right side) of baboons. Recording site marked by stippled area which corresponds to the lowest threshold focus for flick movements of the thumb elicited by 5 msec anodal pulses. *B*, diagrammatic parasagittal section through pre- and postcentral gyri of arm area of a baboon's brain with the approximate extent of the motor cortex (area 4) and of the subdivisions of the postcentral gyrus. Area 3a is the specific projection area for low threshold muscle afferents. A representative electrode tract passing perpendicularly to the surface and down to the bottom of the Rolandic fissure is marked by a straight line.

spontaneous spike activity were compared before, immediately after, and about 10 min after injection. Single unit activity evoked by rhythmic passive movements of the hand or fingers or by rhythmic pressure exerted on muscle bellies were sometimes stored on tape for subsequent analysis. The frequency of discharge was recorded by means of a reciprocal time-interval display unit (Kay, 1965).

The pronounced arterial pulsations of the baboon's cortex was reduced by covering the cortex with agar which also protected the surface from drying. Sometimes it was necessary to use a celluloid plate as a pressure foot. Extracellular spike potentials were led via a BAK cathode follower to a Tektronix 121-preamplifier (or directly to the preamplifier) and photographed from the screen of a 565 Tektronix oscilloscope (together with incoming volleys and the stimulating current intensity). The

experiments often lasted longer than 24 hr and care was taken to maintain the body temperature about 37° C and the blood pressure around 100 mm Hg. Excellent conditions of the animals proved to be crucial for the responsiveness of the precentral neurones.

RESULTS

At the beginning of each experiment the precentral gyrus was explored with anodal 5 msec pulses in order to localize the lowest threshold focus for flick movements of the thumb or other fingers. This 'hand focus' and the entry points of subsequent penetrations were marked on a polaroid photograph of the exposed brain surface. Extracellular recordings of neurones were usually limited to a narrow strip (about 8 mm/3 mm) situated immediately in front of the vessels of the central fissure (Fig. 1*A*). Units were recorded at depths ranging from 0·5 mm from the surface down to 8 mm (mean depth 4 mm). As soon as a unit was isolated, it was

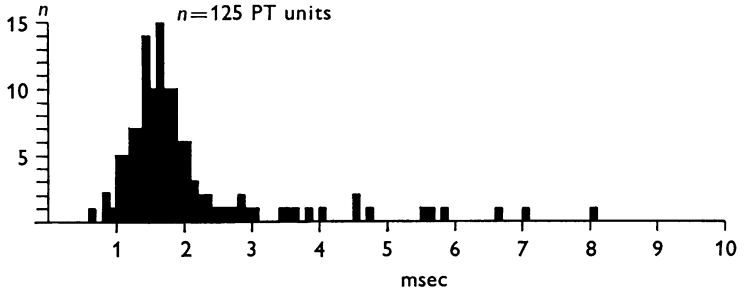

Fig. 2. Latency distribution of precentral units which were activated antidromically by repetitive stimulation (> 100 Hz) of corticospinal axons at C1–2. The division between 'fast' and 'slow' PT cells was made arbitrarily at 2·9 msec.

tested as to whether it was fired by an antidromic volley (trains of about 300/sec). A total of 155 precentral neurones was recorded in this area; 122 units were from baboons, 33 units from monkeys. The responsiveness and latencies of responses were compared in the two species, but since no statistical difference was found, they are treated as one sample. On exploring the cortical hand area, many non-PT neurones were encountered, but usually not recorded. Only a small sample of thirty units was analysed for comparison with the PT neurones and will be described separately.

The afferent input to PT neurones. Fig. 2 shows the antidromic latency distribution of the 125 identified PT units. The division between fast and slow conducting PT neurones was made arbitrarily at 2·9 msec.

Out of 125 PT cells, fifty-six were not responsive to electrical nerve stimulation. However, more than half of these non-responsive neurones were tested at weak intensities only of muscle nerve stimulation in the

early experiments on baboons; moreover, some of these animals had received small doses of pentobarbitone (under these conditions 3a neurones were readily excited). In later experiments, however, in which barbiturates were avoided and stronger stimuli were used to excite additional higher threshold muscle and skin afferents, there was still a large proportion of PT neurones (twenty-five) which were non-responsive to these afferent stimuli. Slowly conducting PT neurones were particularly difficult to excite by afferent stimuli (see below).

Out of the sixty-nine PT neurones responsive to strong peripheral

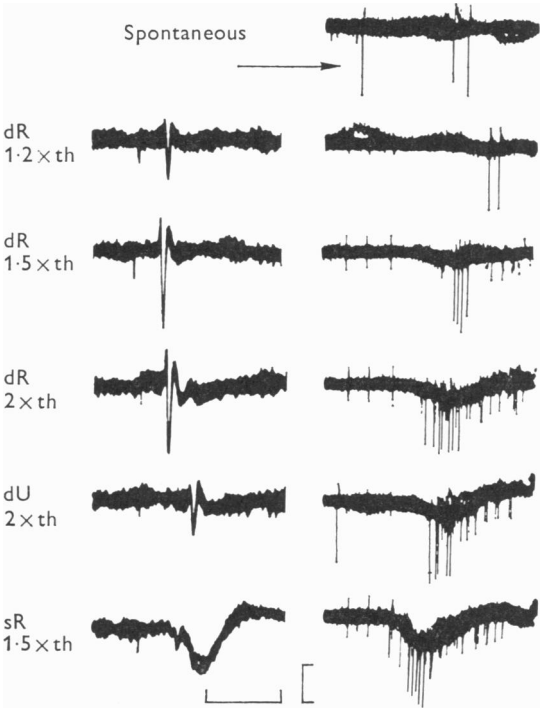

Fig. 3. Discharge pattern of an identified 'fast' PT neurone (large spike). Five superimposed sweeps. Note convergence from deep (motor) radial nerve (dR), deep palmar (motor) branch of ulnar nerve (dU), and superficial (cutaneous) radial nerve (sR). The two spike discharges at 1–2 × group I threshold (1·2 × th) are spontaneous. The threshold for an evoked discharge (large and small spike) was at 1·5 × group I threshold (dR). Note decrease in latency when the stimulus intensity was raised to 2 × group I threshold. Similar discharge pattern to 'deep ulnar' and superficial radial nerve stimulation. The incoming volleys evoked by single pulses at the respective intensity are displayed on the left row. Note that the group I spike (dR) was already maximal at the threshold intensity for eliciting a unit discharge. Time calibration: 10 msec for unit recordings, 4 msec for incoming volley. Voltage calibration: 200 μV.

stimuli (intensity > 2 × group I threshold), thirty-two units were excited by all three nerves tested (deep and superficial radial nerve, deep ulnar nerve); eighteen units had spike responses to stimulation of two nerves, and nineteen units to one nerve only. With one exception all units excited by a deep radial nerve volley were also excited by a superficial radial nerve volley. Convergence from different modalities and from different nerves was thus a characteristic feature for the majority of PT neurones. This is quite in contrast to the strict somatotopy and the lack of modality convergence of 3a neurones studied previously. A representative example of a PT neurone is illustrated in Fig. 3.

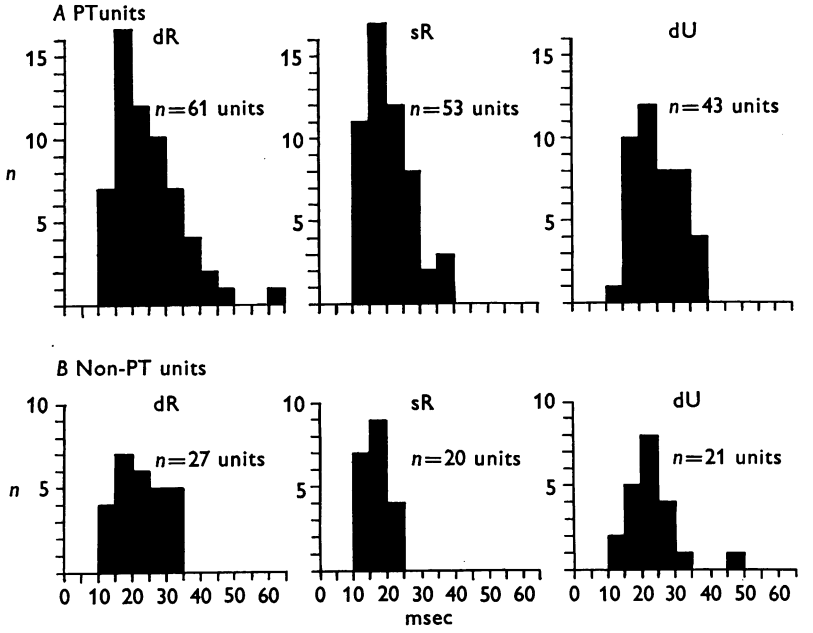

Fig. 4. Latency distribution of precentral units responding to electrical stimulation of the deep radial nerve (dR), superficial radial nerve (sR), and deep ulnar nerve (dU). The mean latencies for identified PT units and non-PT units are listed in Table 1.

Latency histograms for all PT neurones responding to strong electrical stimulation of the three nerves to the hand and forearm are shown in Fig. 4. The latencies were always measured from the first peak of the incoming volley recorded at the cervical cord. The distributions for the different nerves are similar. The mean latencies are listed in Table 1.

On the average, the 3a neurones (excited by volleys just above threshold for the group I fibres) fired at latencies 16 msec (deep radial nerve) and 18 msec (deep ulnar nerve) shorter than PT neurones. The shortest

latencies observed were 5 msec for neurones in area 3a and 12 msec for PT neurones of the precentral hand area.

Are PT neurones influenced by pure group I volleys? Volleys which were just above threshold for a muscle twitch and which produced a group I spike not larger than half of the maximal amplitude (deep radial and deep ulnar nerve), never elicited an overt spike response. Threshold responses appeared in some of the neurones at 1·4–2 × group I thresholds (Fig. 3).

TABLE 1. Mean latencies of precentral cell discharges evoked by peripheral nerve stimulation

	Deep radial nerve	Deep ulnar nerve	Superficial radial nerve
PT cells	$23 \pm 1{\cdot}2$ msec* $n = 61$ units	$25 \pm 0{\cdot}9$ msec $n = 43$ units	$20 \pm 0{\cdot}9$ msec $n = 53$ units
Non-PT cells	$21 \pm 1{\cdot}2$ msec $n = 27$ units	$22 \pm 1{\cdot}5$ msec $n = 21$ units	$16 \pm 0{\cdot}7$ msec $n = 20$ units
Mean difference	2 msec	3 msec	4 msec ($P < 0{\cdot}05$)

* S.E.

Often these spike responses were difficult to ascertain because of the spontaneous activity and the low probability of evoked firing. Therefore poststimulus time histograms were constructed from about 15–20 sweeps and compared with a spontaneous activity occurring during an equal number of sweeps. In a small number of units, the effect of 100 train stimuli eliciting half maximal group I volleys, were analysed on line to detect possible fine modulations of the background spontaneous activity. No effects, excitatory or inhibitory, were seen in any of the units. Fig. 5 shows an example of a unit which exhibited a minimal response to a stimulus of 2 × threshold intensity applied to the deep ulnar nerve. This stimulus strength was well above threshold for the motor nerve fibres and a slow wave followed the group I volley, indicating that high threshold muscle afferents were involved.

It can thus be concluded that pure group I volleys were not effective in modulating the firing rate of PT neurones. Detection of subtle potential changes at the post-synaptic membrane of the PT cells could possibly have been revealed by intracellular recordings. However, the difficulties encountered in preliminary experiments performed together with C. G. Phillips were enormous and the results disappointing. A few impaled neurones were damaged by the penetration and injury spike discharges made an assessment of possible effects of weak nerve stimulation impossible. Moreover, the larger pyramidal cells of the baboon's motor cortex are much further apart than those of the cat's motor cortex and therefore

the chance to puncture a cell body proved to be much smaller than in cats. The initial aim of recording the postsynaptic events intracellularly was therefore abandoned.

Effects on slow conducting PT neurones. Fourteen PT units had antidromic latencies ranging between 3 and 8 msec and were therefore classified as slow PT neurones (Fig. 2). Out of these neurones four only (all from baboons) were responsive to either all three nerves (two cells), or to two

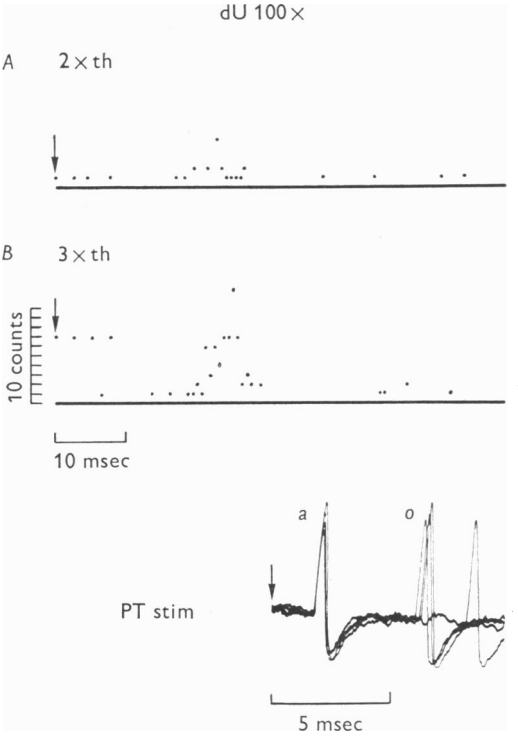

Fig. 5. Poststimulus time histograms of a PT unit discharge. Summation of 100 train stimuli (initial 4 dots) applied to the deep ulnar nerve (dU 100×). Stimulation of the corticospinal fibres at high cervical level (PT stim) produced an antidromic response (*a*) at short and fixed latency and an orthodromic response (*o*) at an unstable and longer latency.

nerves (one cell), or to one nerve only (one cell). The discharge probability was low even when the incoming volleys were maximal and were followed by large slow cord dorsum potentials. An example is shown in Fig. 6. A low responsiveness of slow PT neurones to afferent impulses, as compared with the responsiveness of fast PT cells, has been found in cats (Wettstein & Handwerker, 1970).

Effects of natural stimulation. It was shown in earlier reports (Albe-Fessard & Liebeskind, 1966; Fetz & Baker, 1969; Rosén & Asanuma, 1972) that passive manipulations are an effective stimulus for precentral units. Although this aspect was not a main objective of the present experiments, it was confirmed in most experiments that passive movements of fingers and

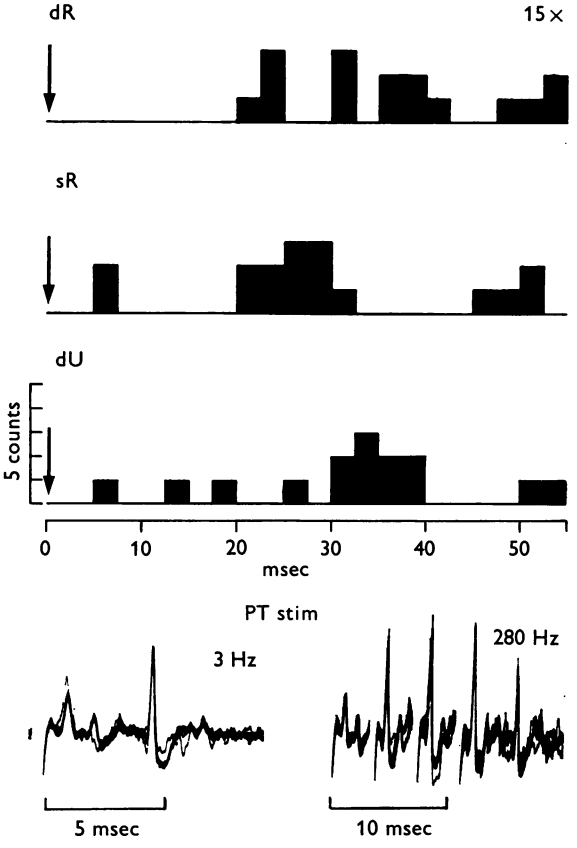

Fig. 6. Poststimulus time histograms of a 'slow' PT neurone. Summation of fifteen electrical stimuli applied to the deep radial (dR), superficial radial (sR) and deep ulnar (dU) nerve. Note low probability of discharges. The intensity of stimulation was maximal for the incoming volleys. Antidromic latency to corticospinal stimulation at high cervical level (PT stim) was 5 msec. Note driving of the unit by a repetitive stimulus (the change in amplitudes of the spike potential is due to summation with field potentials).

wrists could modulate the discharge of PT neurones. In contrast to the behaviour of 3a neurones which typically showed 'dynamic' responses to brisk movements, the evoked activity of PT neurones by passive manipulations was rather of a tonic character in the present experiments. As shown

in Fig. 7, rhythmic manipulations of the thumb generally increased the firing rate without the impulses showing apparent phase relations to the stimulus. Similar tonic discharges were reported by Albe-Fessard & Liebeskind (1966). No attempt was made to test the receptive fields to superficial or deep stimuli.

Effects of succinylcholine on the spontaneous firing rate. It has been reported that injection of succinylcholine produces a short lasting tonic barrage of spindle discharges, the primary endings being much more

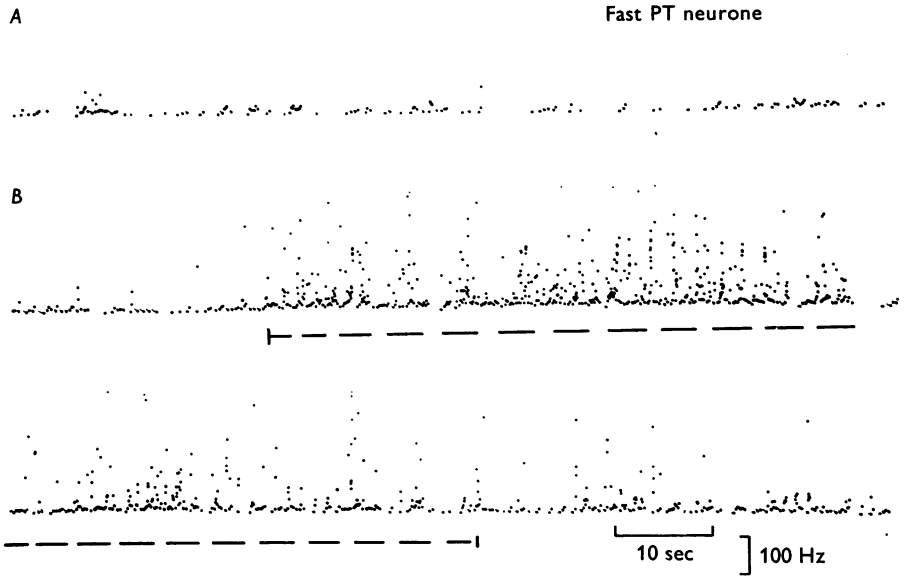

Fig. 7. Effect of 'natural stimulation' on 'spontaneous' firing of a PT neurone. *A*, background impulse activity (displayed as 'instantaneous' frequency). *B*, effect of brisk rhythmic manipulations of the thumb (roughly indicated by interrupted line). Note tonic increase of the firing rate by this manoeuvre.

sensitive than the secondary endings (Fehr, 1965). In four experiments, twelve PT cells were analysed before and after I.V. injection of the drug. No clear-cut effects have been observed. The only cell which might have been slightly accelerated is shown in Fig. 8. The pronounced effect of the same dose on a 3a neurone recorded in the same animal is shown in this same figure. The acceleration of the 3a neurone contrasts markedly with the equivocal effect on the PT cell. The 3a cell gave a typical short latency response to electrical stimulation of the deep radial nerve just above threshold for the group I volley and the electrode track, on subsequent histological examination, was found to pass area 3a. This pharmacological

test is thus another indication that the primary muscle spindle endings do not contribute significantly to the input from muscle afferents to PT neurones. This does not, however, by any means disprove some possible influences from secondary muscle spindle endings.

A comparison of PT neurones with non-PT neurones. In cats, it was shown by Oscarsson & Rosén (1966) that non-PT neurones of the peri-cruciate cortex receive an input from group I afferents. These cells were

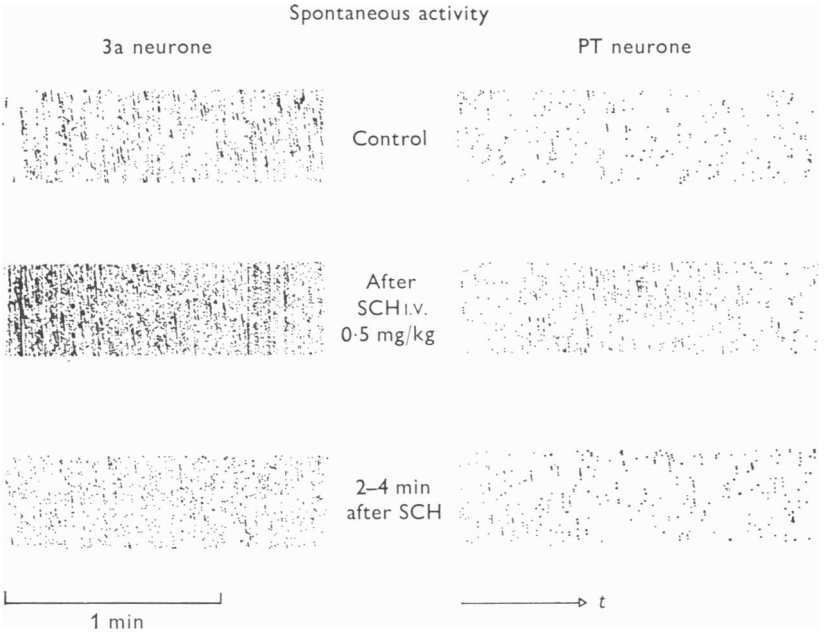

Fig. 8. Effect of intravenous injection of subparalytic doses of succinylcholine (SCH) on a neurone of area 3a (left) and on an identified PT neurone (right) of the same baboon. 'Spontaneous' spike discharges were transformed into dots by means of a Schmitt-trigger circuit, displayed on a continuously running sweep of the oscilloscope (vertical direction), and photographed on slowly moving film (horizontal direction, *t*). Note marked increase of spontaneous activity in the 3a neurone in contrast to the equivocal effect on the PT neurone.

intermingled with PT neurones which, like in the present experiments, received an input from high threshold muscle afferents but not from group I afferents. Investigation of a small sample of thirty non-PT units in the present experiments gave essentially the same results as those of PT neurones. Especially, it was found that pure group I volleys were equally ineffective in producing an overt response. The mean values of latencies to strong peripheral nerve stimulation were slightly lower than those of PT

units, but the difference was not significant for the two muscle nerves (see Table 1); for the cutaneous nerve (superficial radial nerve) the mean latency was 4 msec shorter than the mean latency of PT neurones ($P < 0{\cdot}05$).

DISCUSSION

Electrical stimulation with repetitive shocks applied to the forelimb nerves to the hand and forearm of baboons and monkeys gave the following main results: PT neurones of the hand area exhibit a striking spatial and modality convergence. The responses to stimulation of peripheral nerves clearly have longer latencies than those observed in neurones of the adjacent postcentral gyrus. Furthermore, the synaptic linkage in the afferent pathway is less tight as compared with the lemniscal system. These features all point to a high degree of sensory integration.

Recent experiments in monkeys (Asanuma & Rosén, 1972; Rosén & Asanuma, 1972; Doetsch & Gardner, 1972) and man (Goldring & Ratcheson, 1972) suggest, however, that there is a close input-output relation between limb parts and the motor cortical colonies responsible for moving these limb parts. Thus, units firing prior to a voluntary hand movement were also activated in response to the same passive movement (Goldring & Ratcheson, 1972). There is growing evidence that the motor cortex is 'interested' in proprioceptive feed-back (Albe-Fessard & Liebeskind, 1966; Fetz & Baker, 1969; Rosén & Asanuma, 1972), but these previous observations do not allow one to analyse the 'directness' of the proprioceptive afferent pathway to the motor cortex. Latency measurements from evoked potentials are not considered here because it is hard to avoid contamination of responses in the precentral gyrus from activity in the postcentral gyrus.

It was found in previous experiments (Phillips *et al.* 1971) that area 3a receives a powerful, short latency projection from low threshold muscle afferents of the hands of baboons. This area exhibited a strict somatotopic organization without convergence from cutaneous afferents. At first sight it would seem reasonable to assume that the adjacent motor cortex is utilizing these messages arriving in area 3a. However, the present results indicate that, although the PT neurones are sensitive to muscle stretch, it seems unlikely that the low threshold afferents from the primary muscle spindles are involved. 'Pure' group I stimuli, even if applied repetitively at high frequency, were not capable of influencing PT cell activity. A modulation, excitatory or inhibitory, of spontaneous discharges was not disclosed even if averaging procedures were used. Responses usually occurred not below 1·4–2 × group I threshold. It is true that at this intensity the group I volley is usually not yet maximal and a marginal effect of group I afferents (which would require a high degree of spatial summation) can therefore

not be entirely excluded. Sensitivity of PT neurones to stretch seems however much more likely to depend on the activation of afferents from the secondary muscle spindle endings. The insignificant role of the muscle spindle primaries is furthermore indicated by the lack of effect of succinylcholine (whereas this drug powerfully excited neurones of area 3a). It would be important to supplement these results by controlled adequate stimulation of the primary spindle endings by low amplitude vibration or muscle stretch as was performed in the previous study on 3a neurones. Alternatively, the PT neurones could be tested with and without group I muscle afferents, the latter being eliminated during a DC anodal block leaving the thinner group II afferents intact (Mendell & Wall, 1964; Manfredi, 1970).

Do these facts allow us to conclude that area 3a is not functionally related to the motor cortex? Anatomically, the projection of area 3a has not yet been fully established. Some preliminary experiments in cats (Künzle, H. and Wiesendanger, M., unpublished) reveal that small electrolytic lesions in electrophysiologically identified areas which receive low threshold muscle afferent input, do produce some degeneration in area 4.

With this one must remember that area 3a might receive an input also from group II afferents. This question was not studied in detail in previous experiments reported by Phillips *et al.* (1971); but there was some indication of a participation of group II fibres: the decay of evoked potentials was prolonged if stimulus intensities higher than two times group I thresholds were used. It is therefore possible, but not yet proven, that responses of neurones in area 4 to higher threshold muscle afferents are relayed via area 3a. The delay between the earliest responses to group I stimulation in area 3a and the earliest responses to group II stimulation in the motor cortex are about 7 msec. The mean delay between 3a responses and precentral responses is, however, 16–17 msec and this seems rather long for a simple relay in area 3a for proprioceptive impulses conveyed to the motor cortex.

One alternative pathway would include the cerebellum. There are no reports on the timing of Purkinje cells or nuclear cerebellar cell discharges to muscle afferent stimulation in monkeys. In cats (Eccles, Faber, Murphy, Sabah & Táboříková, 1971), responses of Purkinje cells to forelimb muscle nerve stimulation occurred at latencies of the order of 10–15 msec and most responses were obtained at more than two times group I thresholds. The responses of nuclear cells will have shorter latencies and the pathway from the deep nuclei to the motor cortex via the thalamus might be fast. Thus, at least part of the responses recorded within the motor cortex might have been relayed via the cerebellum.

These possibilities still leave open the question, where the massive input of group I muscle afferents to area 3a is further utilized, if not in the motor cortex. One possibility is that area 3a projects back to subcortical structures. In cats, Gordon & Miller (1969) made the discovery that most corticofugal cells to the dorsal column nuclei are located in area 3a. The functional significance of such a feed-back loop is obscure. It was shown in the previous study on baboons (Phillips *et al.* 1971) that area 3a does not send axons down to the spinal cord. Also it was recently reported by Rosén & Asanuma (1972) that micro-stimulation of area 3a does not produce movements. It is likely (preliminary data by Künzle, H. and Wiesendanger, M., unpublished) that area 3a has also a projection to area 6. Micro-stimulation experiments might help to further elucidate the connectivity of this area.

It was said in the introduction that muscle spindle endings might act as sensors in a load compensating 'pyramidal reflex'. It appears now unlikely that an oligosynaptic pathway from the primary muscle spindle endings subserves such a servoloop. The present findings of a fairly powerful input from higher threshold muscle afferents, however, leaves the possibility open that signals of mismatch between 'intended' and actual muscle length are provided by secondary muscle spindle endings. The pathway to the motor cortex is more complex and slower than would have been expected for a simple transcortical load compensating reflex.

It has been found in several earlier reports that the motor cortext of primates (Hirsch & Coxe, 1958; Zimmerman, 1968; Kruger, 1956) and especially also PT cells (Rosén & Asanuma, 1972) receive a cutaneous afferent input; this was confirmed in this study. Most recently, it was shown by Rosén & Asanuma (1972) that receptive fields of precentral cells activated by tactile stimuli were concentrated on the glabrous volar surface of the hand and were within cortical efferent zones, whose electrical micro-stimulation produced finger flexion. It was proposed that this cortical loop could provide the neuronal base for the instinctive grasping reaction. In addition to this tactile input from the glabrous skin, afferents from the hairy skin must also be involved since electrical stimulation of the superficial radial nerve evoked field potentials in Rosén & Asanuma's experiments as well as unit discharges in the present experiments. This input is probably from higher threshold cutaneous afferents. As to the latencies of cutaneous field potentials, it was claimed by Asanuma & Rosén (1972) that they were the same in the pre- and the postcentral gyrus. Cooling the region around the focus of postcentral evoked potentials, did not change the latency and amplitude of the precentral evoked response, and this was taken to indicate that the pathway to the precentral cortex was independent from the postcentral gyrus. The present findings on the

latencies of single unit discharges of precentral cells to superficial radial nerve stimulation are not in agreement with this interpretation. The latencies of unit discharges were more than two times longer than those found in area 1 and 3b (see Text-fig. 3 in Phillips *et al.* 1971). Cooling of a restricted region of the postcentral gyrus does not exclude the possibility that the early components of the evoked potentials in the precentral gyrus might have their sources in postcentral regions.

A convergence from higher threshold skin and deep afferent fibres to the motor cortex might also be looked at in a different functional context: In cats, it is well known that strong synchronized peripheral volleys produce a generalized discharge of both PT and non-PT neurones. It was proposed that these discharges may be the neuronal basis of a general startle reaction; the motor effects are greatly enhanced by chloralose but are also present in curarized animals (Buser & Ascher 1960).

As has been pointed out by Konorski (1970) lesions in area 6 ('premotor cortex') of the human brain result in a 'dramatic disintegration of skilled movements' i.e. in an apraxia. In Konorski's opinion area 6 is the main locus of integration for kinesthetic input and is therefore responsible for perception of movements. A study of proprioceptive input to neurones of area 6 of primates remains to be undertaken.

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