Neuronal activities in the primate motor fields of the agranular frontal cortex preceding visually triggered and self-paced movement*

K. Okano and J. Tanji

Department of Physiology, School of Medicine, Hokkaido University, Kita 15, Nishi 7, Sapporo 060, Japan

Summary. Single cell activity was examined in the three motor fields of the monkey frontal cortex with the aim of comparing the neuronal activity preceding movements triggered by a visual signal to that preceding nontriggered (self-paced) movements. The following findings emerged from this study. 1. Neuronal activity changes were observed at two different phases in relation to the movement onset; the short-lead type observed within 480 ms prior to the movement onset and the long-lead type, beginning earlier (typically 1 to 2 s). 2. Neurons in both the supplementary motor area (SMA) and premotor area (PM) exhibited the short-lead activity changes prior to the triggered and self-paced movement. Their magnitudes were similar in 63% of SMA and in 36% of PM neurons, whether the movement was triggered or self-paced. 3. SMA neurons, as a whole, were not less active before the triggered than self-paced movement. 4. On the other hand, as many as 92 PM neurons (61%) were related exclusively or peferentially to the triggered movement. 5. The majority of precentral motor cortex (MC) neurons exhibited similar activity changes before the two modes of movement initiation. 6. The long lead type of activity changes were observed mainly prior to the self-paced and much less frequently before the triggered movement. They were particularly abundant among SMA neurons. These results do not support the simple dichotomy hypothesis that SMA primarily takes part in self-paced movement and PM is only involved in visually triggered movement. However, PM neurons show relatively more prominent responses to the visual trigger signal and SMA neurons are intimately related to a long-lasting process leading to initiation of the self-paced movement.

Key words: Supplementary motor area – Premotor cortex – Precentral motor cortex – Visually triggered movement – Self-paced movement

Introduction

Several lines of evidence have accumulated to indicate the existence of at least two nonprimary motor fields in front of the precentral motor cortex (MC) (for review, see Humphrey 1979; Wiesendanger 1981; Wise 1985): the lateral portion of Brodman's area 6, frequently referred to as the premotor area (PM), and its medial portion, defined as the supplementary motor area (SMA). Although PM and SMA have a number of properties in common (Kurata and Tanji 1986), their differences have been inferred from a phylogenetic study (Sanides 1964), from histological studies employing tracer techniques (Schell and Strick 1984), from clinical observations on localized cerebral lesions (for review, see Goldberg 1985) and from studies utilizing measurements of cerebral motor potentials (Deecke and Kornhuber 1978; Libet et al. 1983) as well as regional cerebral blood flow (Roland et al. 1980a, b). On the basis of these reports, a hypothesis has been proposed that SMA takes part in self-initiated movement whereas PM is involved in movements guided or triggered by sensory signals (Eccles 1982; Evarts and Wise 1984; Goldberg 1985; Rizzolatti et al. 1983). This hypothesis pointed to a need for experiments designed specifically to test its validity. Thus, the first aim of the present study was to compare the neuronal activity in SMA and PM in animals performing both sensory signal-triggered and self-paced movements.

Recent reports on the precentral motor cortex (Tanji and Kurata 1982; Lamarre et al. 1983) have shown that the neuronal activity preceding hand movements triggered by visual, auditory or som-esthetic signals is virtually identical, indicating that the premovement activity of MC neurons do not exhibit the modality specificity commonly observed in the cerebellar nucleus (Chapman et al. 1986) or in SMA and PM (Tanji and Kurata 1982; Kurata and Tanji 1986). These findings led to the next question of whether any MC neurons exhibit selective relation to self-paced as opposed to signal-triggered movements, which constituted the second aim of the present study. A preliminary account of this study was published elsewhere (Okano and Tanji 1986).

Methods

Behavioral paradigm

Three male Japanese monkeys (Macaca fuscata) were used in the present experiments. Each was seated in a primate chair and trained to perform both a signal triggered and self-paced key press movement. Both upper extremities were rigidly fixed in L-shaped plastic casts with the elbow flexed at 90°. Movements of the shoulder joints were prevented by separate casts. A key was attached to the distal end of the forelimb cast to be pressed by flexion of fingers and wrist. The task sequence was initiated when a laboratory microcomputer detected the release of the key, which was the start of a hold period during which the animal was required not to press the key. In 50% of the task sequences a red LED on a panel 20 cm in front of the animal came on 2.5 to 4.0 s after the onset of the hold period (pseudorandom time sequence). This indicated that the monkey had to press the key within 800 ms after the red signal in order to receive a reward of apple sauce. In the other 50% of the sequences there was no red signal. In that case the animal was required to wait until at least 5 s after the onset of the hold period, after which the key press was rewarded. No requirement as to the monkey's reaction time was made except for the minimum wait period of 5 s; the three monkeys' mean reaction times (and their SD) were 5.9 ± 2.1, 6.4 ± 2.7 and 6.9 ± 3.3 s. This latter mode of key press was defined as self-paced in the present experiments. All of these sequences of the motor task were controlled by the laboratory microcomputer.

Data recording and processing

After monkeys learned and performed the task stably with more than 95% success rate, a stainless steal recording chamber (32 × 45 mm) was attached to the skull under aseptic conditions. During the surgical operation monkeys were anesthetized by ketamine hydrochloride and sodium pentobarbital. Conventional chronic single-cell recording methods were employed (Evarts 1968). Glass-insulated platinum iridium or Elgiloy alloy microelectrodes (with 2.0–3.1 MΩ resistance) were driven by an electronic stepping microdrive (MO-951, Narishige) for extra-cellular recording. The same electrode was also used for intracortical microstimulation. A train of 12 cathodal pulses of 0.2 ms duration at 333 Hz was applied at an intensity of less than 50 μA through a constant-current stimulator.

On-line analysis of the neuronal discharge was made by using a laboratory computer (243-System, SORD). The activity over 20 trials was aligned with either the signal or the movement onset and displayed as perievent raster displays. The time of closing of the key switch was defined as the movement onset. Perievent time histograms were also constructed with bin widths ranging from 2 to 100 ms (usually 20 ms), providing a basis for detecting the movement-related activity changes. The neuronal activity was judged to be significantly related to a movement if the number of discharges during at least two consecutive 20 ms bins among 24 bins (totaling 480 ms) preceding the movement onset deviated by more than 3 SD of the mean value calculated during a control period of 1280–640 ms preceding the movement. This criterion was employed to define the short-lasting premovement activity changes (short lead type). The choice of 480-ms preceding time was arbitrary but seemed appropriate on the basis of the distribution of onset times of the short-lead activity changes (see Results). In addition to this type, some neurons had more long lasting activity changes prior to the movement onset. In order to detect these long lasting changes, the control period was set at an interval of 480–1120 ms after the start of the hold period. If the number of discharges during at least two consecutive 20-ms bins among 45 bins covering a period of 1380–480 ms preceding the movement onset deviated by more than 3 SD of the mean value calculated during the control period, the activity change was defined as the long-lead type. The magnitude of premovement activity changes was defined as the absolute number of discharges during the premovement period (480 ms for the short lead and 900 ms for the long lead type) minus the background discharges calculated during the control period. If the premovement activity change before the triggered movement was greater than before the self-paced movement by more than 100% or vice versa, the neuronal activity was judged to be preferential.

Muscle activity was monitored from extensor and flexor muscles of fingers, wrist and elbow and also from the deltoid, supra- and infraspinatus, trapezius, pectoralis, serratus, paravertebral and hip muscles with tungsten wire, silver wire or surface electrodes. The EMG was full-wave rectified, converted from voltage to frequency, and analyzed in the same manner as the discharges of single neurons. AC-coupled recording of the electrooculogram (EOG) was also obtained with surface electrodes to monitor saccadic eye movements. In one monkey, a stimulating electrode was permanently implanted in the ipsilateral medullary pyramid at level P-2, L-1 of the Horsley-Clarke coordinate for identification of pyramidal tract neurons (PTNs). Their antidromic responses and latencies were confirmed by the spike collision method.

Histological studies

The monkeys were deeply anesthetized with an overdose of pentobarbital and perfused through the heart with saline followed by 10% formalin with 3% potassium ferrocyanide. The brain was removed from the skull after marking the location of the recording chamber and noting cortical landmarks, photographed, sectioned parasagittally at 50 μm on a freezing microtome, and stained with thionin. Reconstruction of electrode track was attempted with the aid of microlesions and iron deposits (formed by passing 10–15 μA DC current for 10–15 s during recording) as reference points.

Results

Muscle activity

Great care was taken to train the monkey to perform the key press movement in such a manner that (1) the
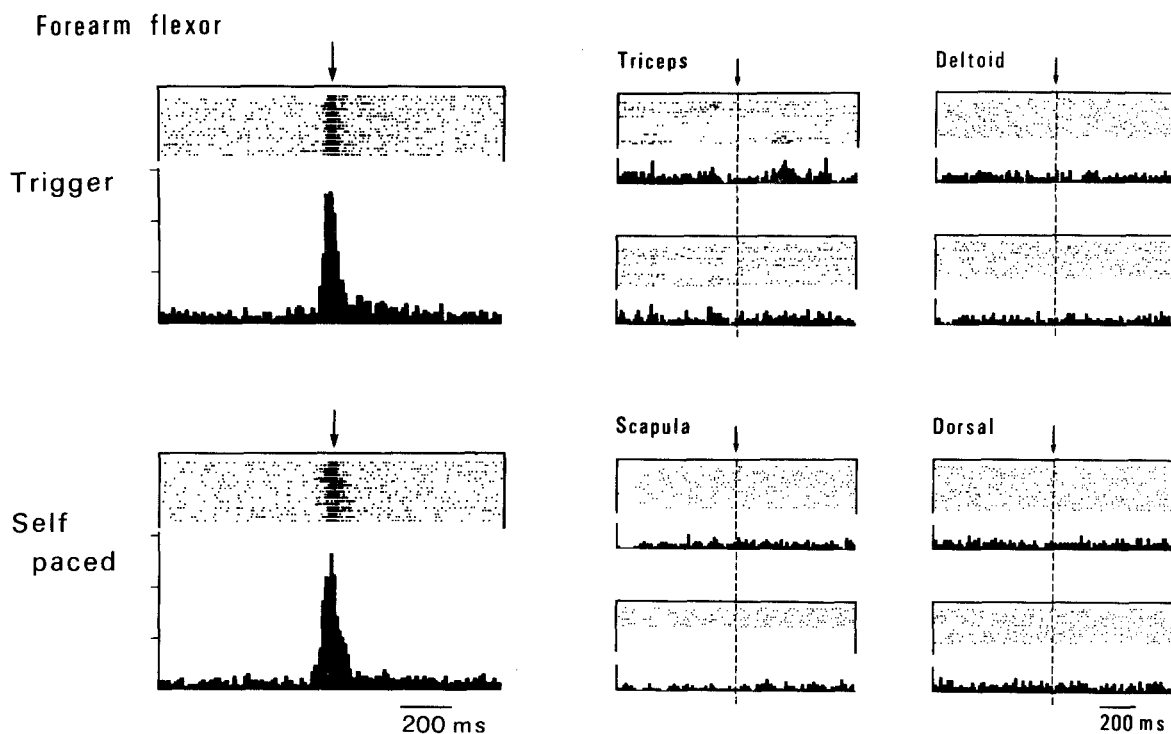
Fig. 1. EMG activity in the four forelimb muscles and the back muscle: Forearm flexor, flexor carpi ulnaris; Triceps, triceps brachii; Deltoid, deltoideus; Scapula, supraspinatus; Dorsal, paravertebral muscle. EMGs are rectified, digitized and displayed as rasters. Each line of the raster denotes individual trials. Dots in the raster displays are summated in histograms below each raster. Activities in visually triggered and self-paced key press movements are indicated in the upper and lower part of each pair of display for the 5 muscles. Arrows indicate the onset of each movement

muscle activity in the triggered and self-paced movement was similar, (2) no overt movements were initiated during the hold period before either the signal triggered or self-paced key press and (3) the muscle activity was limited to distal forelimb muscles. EMG in forearm flexors was monitored either with surface electrodes or wire electrodes inserted in Mm. flexor digitorum sublimis, flexor digitorum profundus, flexor carpi ulnaris and flexor carpi radialis during the task performance. In all of these muscles, the magnitudes of perimovement activities in the triggered key press did not differ from that in the self-paced key press by more than 33%, as exemplified in Fig. 1 (left), although the activity in the former tended to be more synchronized than in the latter. The onset times of the M. flexor digitorum sublimis activity relative to the movement onset, analyzed in the three animals, are indicated in Table 1. In the first and second monkeys, EMG electrodes did not detect any activity changes in any limb or body muscles during the hold period. In the third monkey, some muscle activity was at times detected in the forearm muscle during the hold period. In that case, the neuronal recording was terminated and no data was taken. In the first two monkeys the key press was

Table 1. Onset times of M. flexor digitorum sublimis activity relative to the movement onset in typical EMG recording sessions in three monkeys (mean ± SD in ms)

	Triggered	Self-paced
Monkey 1	52 ± 8	58 ± 11
Monkey 2	46 ± 7	55 ± 10
Monkey 3	57 ± 9	64 ± 17

performed with hand and digit muscles, as far as could be judged by EMG recordings. As shown in Fig. 1 (middle and right), upper arm, shoulder and body muscles were not active bilaterally. In the third monkey the right triceps and/or brachioradial muscles were active during the key press. However, the onset of their activity was later and the magnitudes were smaller than those of forearm flexors. These EMG findings indicated that the key press was performed exclusively or at least predominantly by distal forelimb muscles and their activity was withheld during the hold period. All monkeys used their right hand to press the key. In addition, the first monkey was retrained to use its left hand after completion of the left cerebral hemisphere recording. One month of
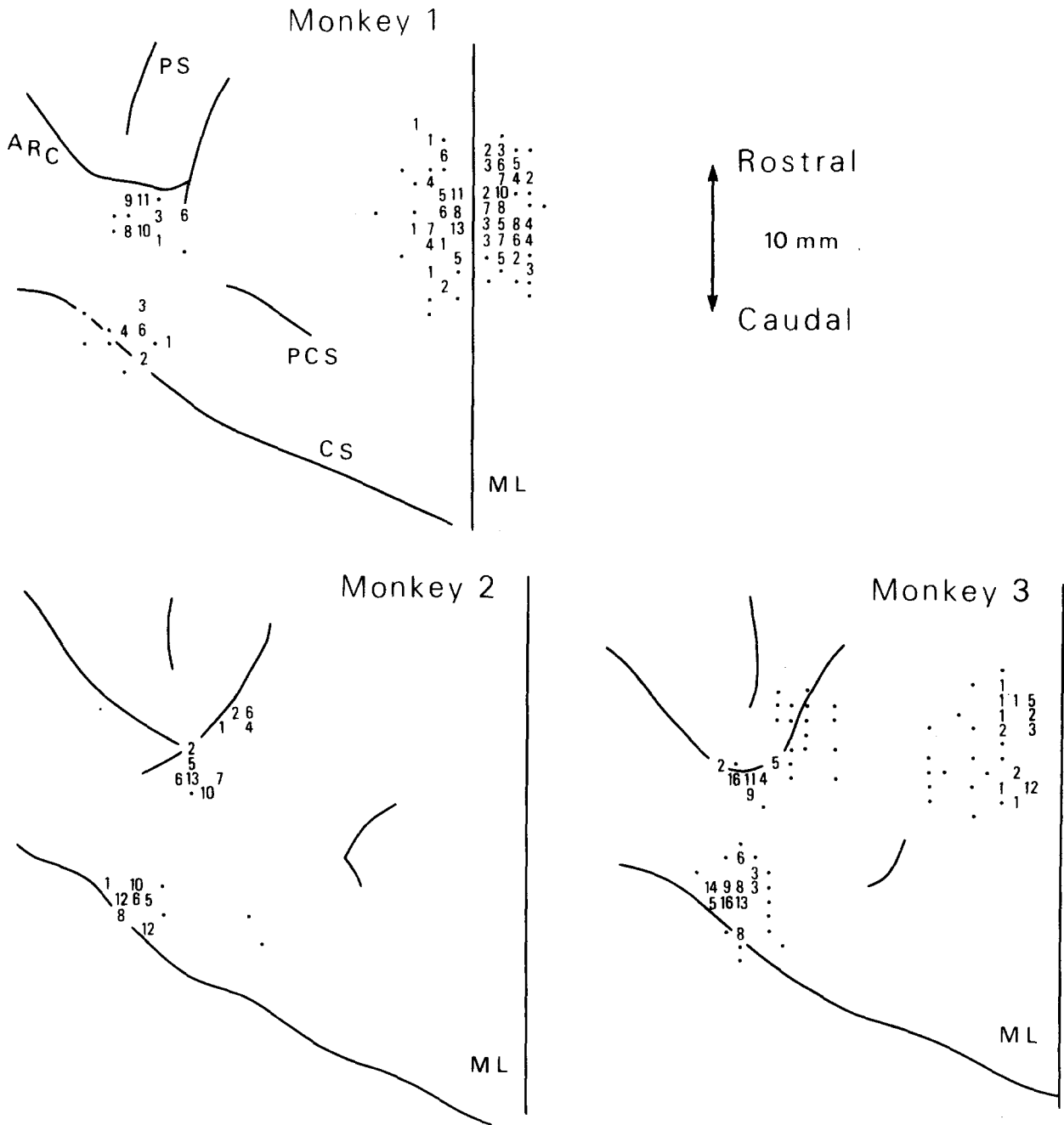
158

Fig. 2. Surface maps of the frontal cortex of 3 monkeys indicating sites of microelectrode entry and numbers of the premovement active neurons recorded at each penetration sites and fully analyzed for the quantitative study. Dots indicate the sites where the cortex was penetrated but no task-related neurons were obtained. The left hemispheres of the three monkeys and the right hemisphere of one monkey were penetrated while monkeys were using only the contralateral hand. The abbreviations for sulci are CS, central sulcus; PCS, precentral sulcus; ARC, arcuate sulcus; PS, principal sulcus. ML indicates the medial limit of the cortical dorsal surface

retraining was required to achieve motor performance equivalent to that of its right hand.

Cortical field determination of recording sites

Recording sites were determined to be in MC, PM or SMA according to recently proposed criteria (Sessle and Wiesendanger 1982; Weinrich and Wise 1982; Wise 1985), namely the density of giant pyramidal cells in layer V and the presence or absence of microstimulation effects with small currents. The areas assigned to PM correspond largely to forelimb areas of PM previously determined physiologically (Kubota and Hamada 1978; Weinrich and Wise 1982;
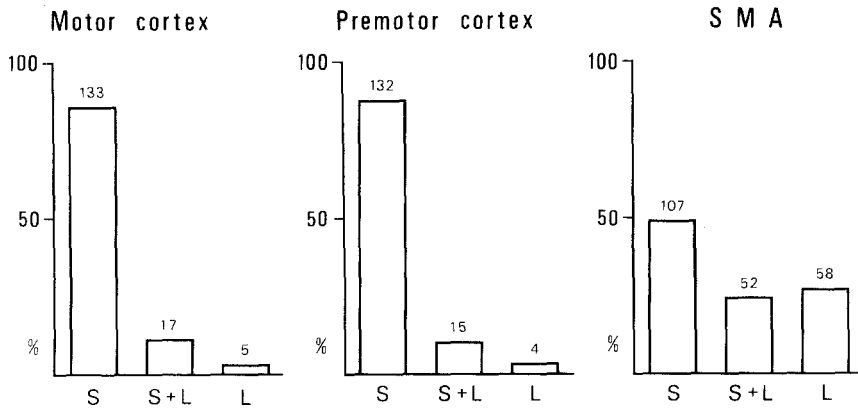
Motor cortex   Premotor cortex   S M A

Fig. 3. Histograms indicating frequencies of occurrences of the short-lead and long-lead types of the neuronal premovement activity changes in the three motor areas. Numbers of neurons exhibiting the short only (S), long only (L) and both (S+L) types of activity changes are indicated on top of each histograms. Results obtained in both self-paced and triggered movements are included. Ordinates denote the relative frequencies of occurrences in percentages
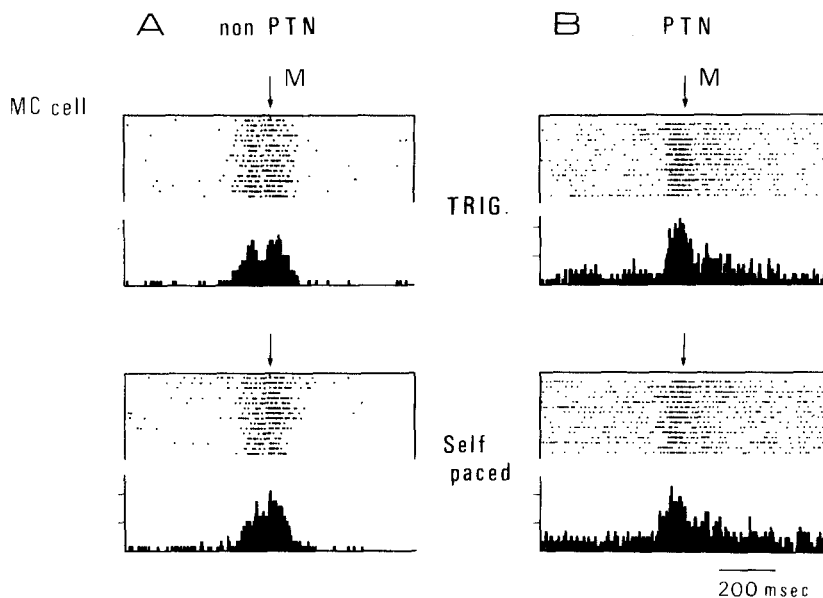

Fig. 4A, B. Discharge of motor cortex neurons exhibiting the typical short-lead type of premovement activity changes. Neuronal discharges are indicated as dots and are aligned on the onset of the triggered (upper part) and self-paced (lower part) key press movement. The movement onsets are indicated with arrows. Each line of the raster denotes individual trials. Examples of a non PT neuron and a PT neuron are displayed in A, B. Tick marks on the ordinate of each histogram denote 100 imp/s

Kurata et al. 1985) or histologically (Muakkassa and Strick 1979; Godschalk et al. 1984). Also, the areas assigned to SMA correspond to forelimb areas of SMA previously determined physiologically (Brinkman and Porter 1979; Tanji and Kurata 1982) or histologically (Muakkassa and Strick 1979; Murray and Coulter 1981). Figure 2 indicates points of microelectrode entry in the cortical surface of three monkeys. Three left hemispheres plus the right hemisphere of the first monkey were surveyed. Numbers at each point denote the number of neurons which were recorded long enough for the statistical analysis stated above and found to exhibit activity changes in the premovement period.

Neuronal activity in the precentral motor cortex

One hundred and fifty-five neurons recorded from MC were found to change their activity prior to the

movement onset. In 133 (86%) of them the activity increase (89%) and decrease (11%) was classified as short-lead type according to the criteria described in the method section. The neuronal premovement lead times ranged from 64 to 312 ms with their mean and SD of 124 ± 39 in the visually triggered movement. When the movement was self-paced, they ranged from 58 to 352 ms with their mean and SD of 131 ± 42. The frequency of occurrence of this type of short-lead activity changes is indicated as S in the left part of the histogram drawn in Fig. 3. In five neurons the activity changes started more than 1 s prior to the movement onset and classified as long-lead type (L in Fig. 3). The remaining 17 neurons exhibited both the long- and short-lead type of activity changes (S+L).

In most of the short lead neurons (134, 89%) the activity changes preceding the signal-triggered and self-paced movement were similar as exemplified in Fig. 4 (discharge activity of a non-PTN and a PTN is shown in A and B). In 6 neurons the short-lead
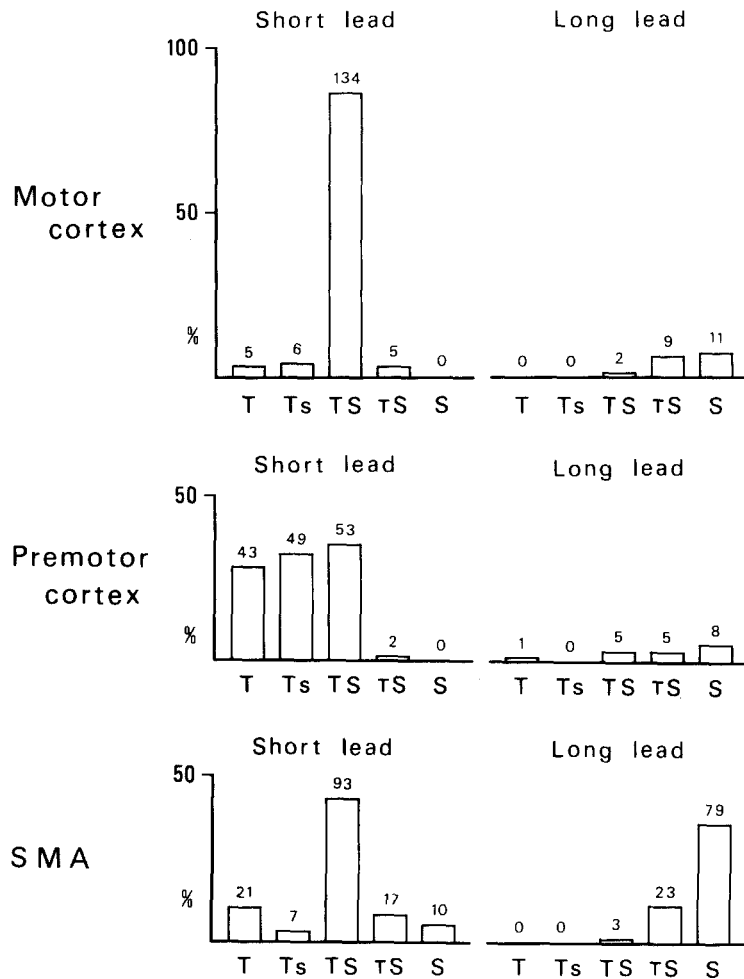
Fig. 5. Histograms showing frequencies of occurrences of neuronal activity changes falling into 5 categories according to relative magnitudes prior to the triggered as compared to self paced movement. Data obtained from the precentral motor cortex, premotor cortex and the supplementary motor area are displayed in the top, middle and bottom part of the figure, respectively. Classifications of neuronal activity changes: T and Ts, exclusive and preferential relation to the triggered movement, respectively; TS, similar activity changes before two types of movement initiation; tS and S, preferential and exclusive relation to the self-paced movement. The short- and long-lead premovement activity changes are displayed in the left and right half of the figure. Numbers on top of each bar indicate actual number of activity changes of each category. Ordinates indicate the rate of appearance (percentage) of each type of activity changes among neurons belonging to one of the three motor areas

activity was greater prior to the triggered than self-paced movement and in 5 neurons the activity changes were greater with self-paced movements. In the remaining 5 neurons the activity increase was observed only prior to the triggered movement. The frequency of occurrences of such relative magnitudes of premovement activity changes are indicated in the top left histogram of Fig. 5. The 5 neurons possessing exclusive relation to the triggered movement were all recorded in the superficial cortical layer, where neuronal spike heights were generally small and field potentials evoked by the pyramidal tract stimulation were minimal.

As stated above, 22 MC neurons exhibited the long-lead type of activity changes long before 480 ms prior to the movement onset, a period when no activity changes were recorded from any muscles. In most (18) of them the activity changes lasted more than 1 s. Eleven of the long lead activity changes were observed prior to both the triggered- and self-paced movement. In 9 of the 11 neurons the activity changes were greater preceding the self-paced than

triggered movement. In a separate group of 11 neurons the activity changes were observed only prior to the self-paced movement (see top right of Fig. 5).

Fourteen of the movement-related MC neurons were identified as PTNs by antidromic PT stimulation. All of them exhibited the short-lead activity changes, whose magnitudes prior to the triggered and self-paced movement were invariably similar. One PTN had, in addition to the short-lead activity, the long-lead activity increase whose magnitude was greater prior to the self-paced movement.

Neuronal activity in the premotor cortex

One hundred and fifty-one neurons recorded from PM were found to change their activity prior to the key press. Of these, 132 neurons exhibited the short lead (S in Fig. 3) and 4 neurons exhibited the long-lead (L) activity changes. The remaining 15 neurons had both types of activity changes (S+L).
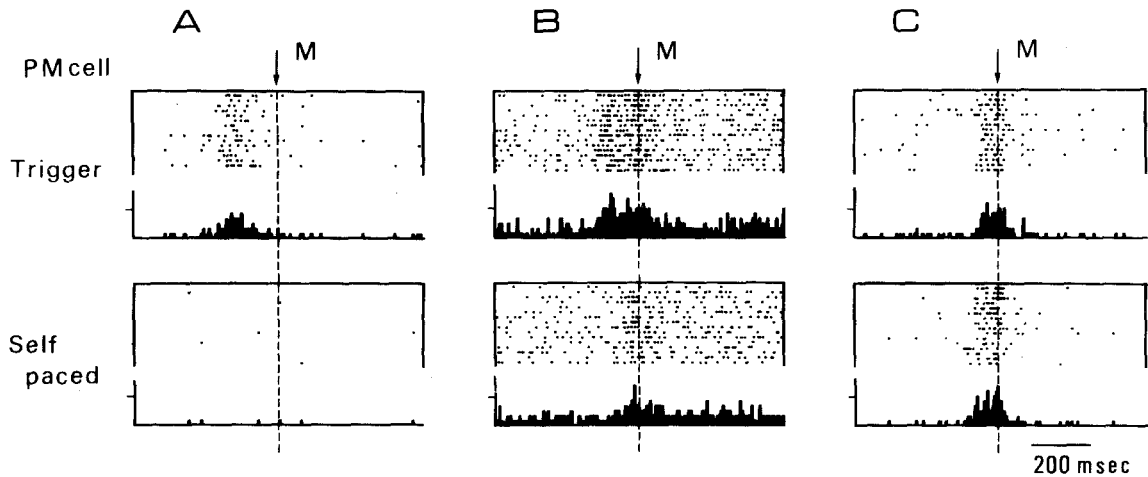
A   B   C

Fig. 6A–C. Discharges of three types of neurons typical of PM. Formats for the display are the same as in Fig. 4. The neuron in A increased its discharge prior to the triggered but not to the self-paced movement (exclusive relation). In B the activity increase is greater before the triggered movement (preferential). In C the magnitudes of activity changes are similar before the two modes of movement initiation
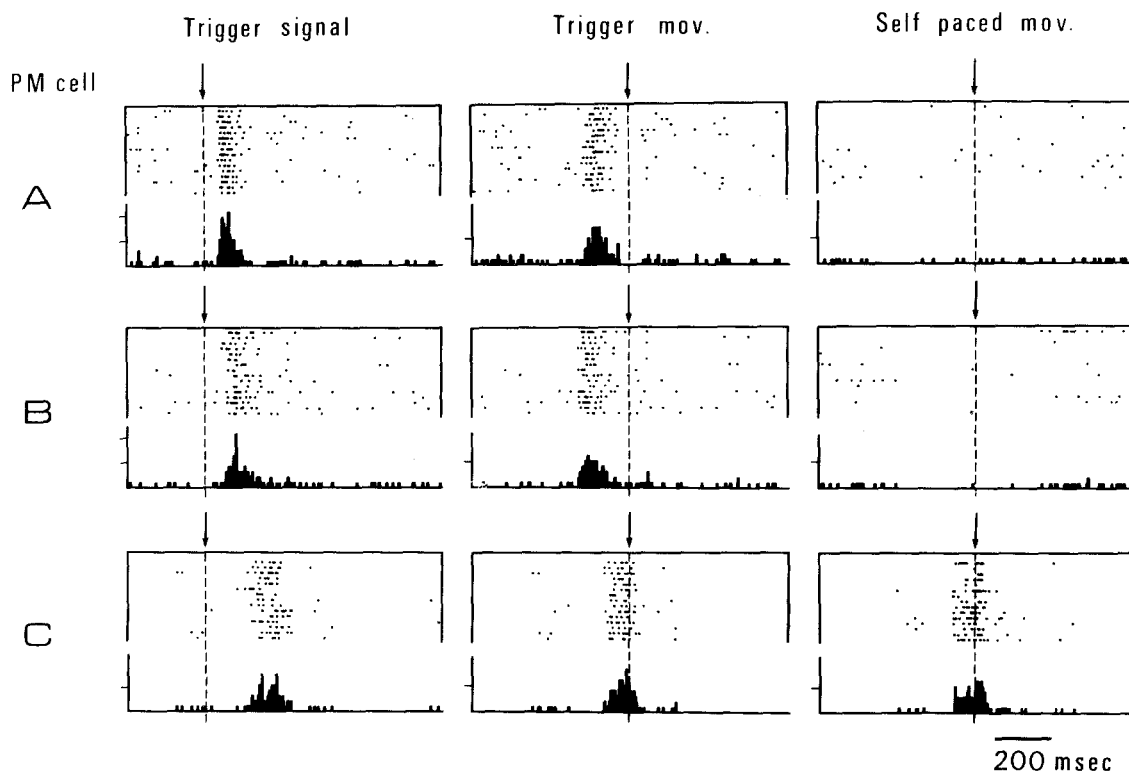

Fig. 7A–C. Discharge of three PM neurons exhibiting three types of time relations to the visual trigger signal and to the movement onset. In the left and middle row of the figure, discharges are aligned on the onset of the visual trigger signal and the onset of the triggered movement, respectively. In the right row, discharges are aligned on the onet of the self-paced movement. The onset of activity increases in neuron A for individual trials are time locked better to the signal onset than to the movement onset, while those of neuron C are better time locked to the movement onsets. In neuron B the onsets are time locked to neither (indeterminant type)

The premovement lead times of the short-lead activity changes ranged from 62 to 352 ms, with their mean and SD of 186 ± 51 in the visually triggered movement. When the movement was self-paced, they ranged from 49 to 380 ms, with their mean and SD of 197 ± 66. In 53 PM neurons, the magnitudes of the short-lead activity changes were similar before the signal-triggered and self-paced movement, just as

Table 2. Correlations between the short-lead PM neuronal types classified according to the relative magnitudes of premovement activity before the triggered as compared to self-paced movement and the neuronal types classified according to the time relations to the trigger signal and movement onset

	T only	Ts	TS	tS	Total
Signal locked	6	3	3	0	12
Movement locked	13	24	32	2	71
Indeterminant	24	22	18	0	64

* Premovement activity types are detailed in the caption of Fig. 5

in the majority of MC neurons. However, in 49 neurons they were greater prior to the triggered than to the self-paced movement. Fourty-three neurons exhibited the short-lead activity changes exclusively prior to the triggered movement. Examples of these neuronal activities, typical of PM, are shown in Fig. 6A–C. Only 2 neurons had greater activity changes prior to the self-paced movement and no neurons had exclusive relation to the self-paced movement (middle left of Fig. 5). In addition to these 145 neurons, 2 atypcial PM neurons were recorded whose activity increased prior to the triggered movement but decreased before the self-paced movement. PM neurons having either preferential or nonpreferential relation to the two modes of movement initiation were often recorded in succession during the penetra-

tion, suggesting clustered localization of each category. However, no trends of preferential cortical distribution were found in the rostrocaudal or mediolateral direction. No particular categories of PM neurons were localized in either superficial or deep layer of the cortex.

In accordance with previous reports, the premovement activity of some PM neurons were time-locked more to the trigger signal onset than to the movement onset, which was a property never observed in MC. Therefore, the activity was classified as signal locked, movement locked or indeterminant according to a statistical method described in a previous report from our laboratory (Kurata and Tanji 1986). Examples of the signal-locked, indeterminant and movement-locked activities are displayed in Fig. 7A–C, respectively. The signal-locked activity was most prevalent among neurons possessing exclusive relation to the triggered movement, whereas the movement-locked activity was most often observed among neurons equally active prior to the triggered and self-paced movement. The correlation between the classification of neurons according to their relations to the movement types and their timing relation to the signal or movement onset is indicated in Table 2.

As stated above, 19 PM neurons exhibited the long-lead type of activity changes. Only one of the 19 neurons had reciprocal relation: its discharge
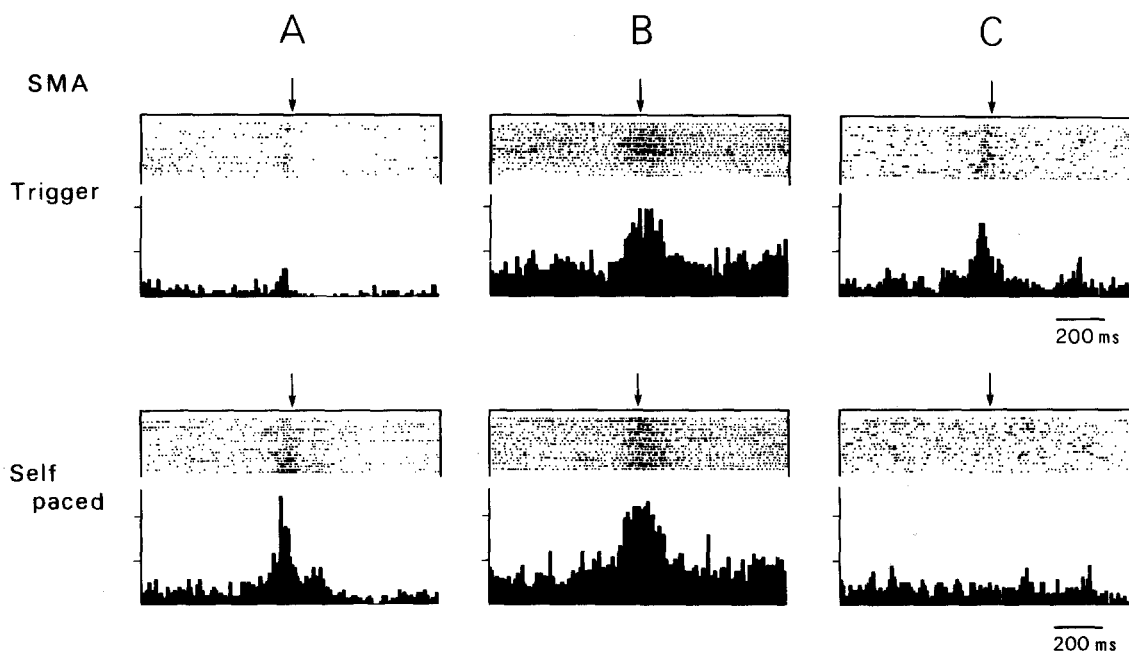

Fig. 8A–C. Discharge of three types of SMA neurons exhibiting different relations to the triggered and self-paced movement. B is an example of the most common type of SMA neurons whose premovement activity is similar before the triggered (upper) and self-paced (lower) movement. In neuron A, the activity is greater prior to the self-paced than triggered movement. The activity of neuron C increased only prior to the triggered movement
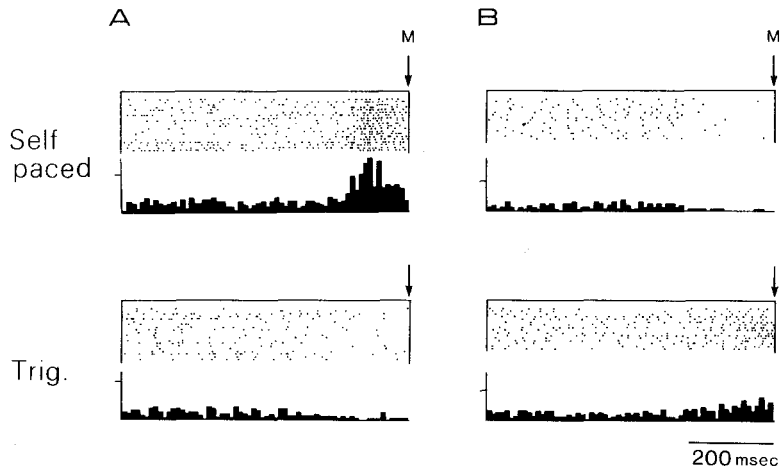
Fig. 9A, B. Discharge of two SMA neurons exhibiting reciprocal relations to the self-paced and triggered movement. In neuron A (left) the discharge increased before the self-paced but decreased before triggered movement. In neuron B (right) the relation is reversed

increased before the triggered and decreased before the self-paced movement. The rest of 18 neurons either increased (12) or decreased (6) their discharge. In 8 neurons the long-lead activity was observed only before the self-paced movement. In 5 neurons the magnitudes of the activity changes were greater prior to the self-paced movement and in another 5 neurons they were similar before the two types of movement. In the remaining one neuron the activity increased only prior to the visually triggered movement. Of these 19 neurons, the activity changes of only two neurons were tightly time locked to the instruction signal.

Neuronal activity in supplementary motor area

Two hundred and seventeen neurons recorded from SMA were found to change their activity prior to the key press. Of these, 107 neurons exhibited the short-lead (S in Fig. 3) and 58 neurons exhibited the long-lead (L) activity changes. The remaining 52 neurons had both types of activity changes (S+L).

The premovement lead times of the short-lead activity changes ranged from 58 to 391 ms, with their mean and SD of 164 ± 49 in the visually triggered movement. When the movement was self-paced, they ranged from 48 to 427 ms, with their mean and SD of 181 ± 58. In 93 SMA neurons, the magnitudes of the short-lead activity changes were similar before either the signal-triggered or self-paced movement and therefore their activity was akin to the majority of MC neurons (Fig. 8B). Seven neurons were more related and 21 neurons were exclusively related to the triggered movement (Fig. 8C, also see bottom left of Fig. 5). In contrast, 17 neurons were more related (Fig. 8A) and 10 neurons were exclusively related to the self-paced movement. Of interest was

Table 3. Correlations between the SMA neuronal types classified according to the relative magnitudes of premovement activity before the triggered as compared to self-paced movement and the neuronal types classified according to the time relations to the trigger signal and movement onset

	T only	Ts	TS	tS	S only	Total
Signal locked	4	3	2	0	0	9
Movement locked	7	3	50	12	8	80
Indeterminant	10	1	41	5	2	59

the presence of 11 neurons exhibiting reciprocal relations. In 6 neurons (whose example is displayed in Fig1 9A) the activity increased prior to the self-paced movement but decreased before the triggered movement. In 5 neurons the relation was reversed as in Fig. 9B.

The SMA activity prior to the triggered movement was also classified as signal-locked, movement locked and indeterminant. The correlation between this classification and the types of relations to the two different modes of movement initiation is indicated in Table 3.

The long lead type of activity changes were observed in 110 neurons, constituting 51% of the 217 task-related SMA neurons. Of these,, 79 neurons exhibited activity changes only prior to the self-paced movement. An example of such an exclusive relation is displayed in Fig. 10A (left column). This SMA neuron increased its discharge starting from about 2 s prior to the initiation of the self-paced movement but not prior to the triggered movement. In 23 neurons the activity changes were greater prior to the self-paced than to the triggered movement, as exemplified in Fig. 10B (right) where the neuronal activity decreased more markedly before the self-paced movement. In 3 neurons the magnitudes were simi-
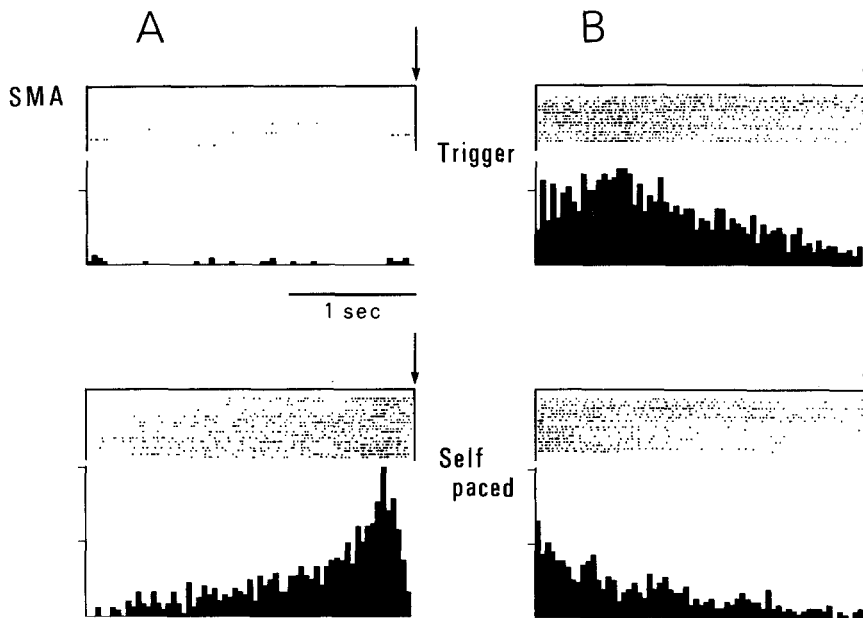
Fig. 10A, B. Examples of the long-lead activity changes in two SMA neurons. In neuron A (left), the discharge increased only prior to the self-paced movement (bottom). In neuron B (right) the discharge decreased more strongly before the self-paced than before the triggered movement

lar. In these 105 neurons classified in Fig. 5, the discharges either increased (89%) or decreased (11%) prior to the two modes of movement initiation. However, in three SMA neurons the discharges increased before the triggered and decreased before the self-paced movement. In the remaining 2 SMA neurons the relation was reversed. Onsets of the majority of the instruction responses were gradual, except in 2 neurons whose response onsets were time locked to the instruction signal.

As among PM neurons, SMA neurons of a particular type were at times recorded in succession during penetration of the cortex but no trends for preferential spatial distribution of any particular properties were found.

Discussion

In the present study, premovement neuronal activity changes were observed at two different phases in relation to the movement onset: the short-lead and long-lead activity. Since they seem to have different functional significance, they will be discussed separately.

The short-lead activity changes were observed within 480 ms prior to the movement onset and seemed closely related to the initiation of phasic muscle activity or to the process of triggering the movement. They were observed in all three of the motor fields prior to both the signal-triggered and self-paced movement. In SMA as well as in PM, the most frequently observed type of neurons exhibited

similar magnitudes of activity changes regardless of whether the movement was triggered or self-paced (see histograms in the left column of Fig. 5). Figure 5 also indicates that SMA neurons are no less active prior to the triggered than the self-paced movement. In addition to the 93 neurons equally related, 28 SMA neurons were exclusively or preferentially related to the triggered movement as opposed to 27 neurons related more to the self-paced movement. Taken together, these findings do not support the simple dichotomy hypothesis that SMA primarily takes part in self-paced movement and PM is only involved in visually triggered movement. The differences in these two areas appear to be more subtle as suggested in two recent review articles (Goldberg 1985; Wiesendanger 1986). Indeed, reports showing participation of at least some part of SMA neuronal activity in visually triggered movement (Tanji and Kurata 1982) and also of PM activity in self-paced movement (Hashimoto et al. 1981; Kurata and Tanji 1986) have appeared in the literature. On the other hand, as many as 92 PM neurons were related exclusively or preferentially to the triggered movement, indicating the presence of a considerable population of PM neurons subserving more roles in the visually triggered movement. These neurons far outnumbered the 2 PM neurons having preferential relation to the self-paced movement. This finding is consistent with a view that PM, with its prominent afferents from parietal association cortex (Petrides and Pandya 1984; Godschalk et al. 1984) plays an important role in initiating visually triggered movement (Kubota and Hamada 1978; Rizzolatti et al.

1981; Weinrich and Wise 1982) or in retrieving a predetermined movement by means of visual cues (Moll and Kuypers 1977; Halsband and Passingham 1982; Rizzolatti et al. 1983; Weinrich et al. 1984).

The long-lead activity changes were observed in the period preceding more than 480 ms (mostly 1 to 2 s, see Fig. 10) prior to the movement onset. They were observed mainly prior to the self-paced and much less frequently before the triggered movement. There are a number of similarity between this neuronal activity and a cortical evoked potential preceding voluntary movements in man (for review, see Haider et al. 1981), a potential especiallly prominent before self-initiated movements and termed the readiness potential. The preponderance of the long-lead activity in SMA is in accord with a proposition (Deecke and Kornhuber 1978; Boschert et al. 1983) that the readiness potential is focused over the region covering the SMA in man. Furthermore, the long-lead SMA activity may correspond to the increase in the regional blood flow of the frontomedial cortex of human subjects during a period when hand movements were conceived but not actually performed (Ingvar and Philipson 1977) or mentally rehearsed (Roland et al. 1980). These findings in monkey and man seem to be in accords with the view (Goldberg 1985) that SMA plays a part in the initiation of movements according to internally organized cues or internal drive. In this respect, two anatomical afferent connections to SMA are of particular interest: namely, the corticocortical input from the cingulate gyrus (Jürgens 1984) and the inputs from basal ganglia by way of the thalamic nucleus, VLo (Schell and Strick 1984; Wisendanger and Wiesendanger 1985). The former input has been implicated in mediating the internal drive for movements originating in the limbic system (Talairach et al. 1983) and the latter input in providing the internally organized motor program (Marsden 1982; Evarts and Wise 1984). However, it should be pointed out that SMA, in addition to the role in internally organized motor preparation for self-paced movements, seems also to take part in preparatory processes for movements triggered by external cues. The SMA activity in preparation for the direction of triggered movements (Tanji et al. 1980) and for the selection of motor acts in accord with the modality of forthcoming sensory cues (Tanji and Kurata 1985) have already been reported.

In the present experiments the long-lead type of activity preceding the visually triggered movement was observed only in a small number of neurons in either PM or in SMA. This may be explained by the fact that no peparatory processes as to the nature of the forthcoming movement was required in the pretrigger period of the present motor task where the monkey had only to press a key in response to a single cue. The PM preparatory activity responding to visual signals which serve as a guiding cue for the forthcoming movement have been abundantly documented (Kubota and Hamada 1978; Godschalk et al. 1981; Wise and Mauritz 1985). It remains to be investigated whether such a visual movement guidance signal would give rise to activity changes in SMA neurons.

In the present study it was found that a majority of MC neurons exhibited an equal amount of pre-movement activity changes regardless of whether the key press movement was triggered or self-paced. This is in contrast to the frequent occurrence of PM (64%) and SMA (40%) neurons whose activities were grossly different depending on whether the movement was triggered or self-paced. In SMA and PM, there were even examples of reciprocal activity changes (see Fig. 10). This finding, in addition to previous reports (Tanji and Kurata 1982; Lamarre et al. 1983) on equi-magnitude reaction to visual, auditory and somesthetic movement-trigger signals further substantiates a view that MC is situated at a later stage of information processing towards movement initiation than SMA (Tanji and Kurata 1982) and PM (Kurata and Tanji 1986) as well as cerebellar dentate nucleus (Chapman et al. 1986), whereupon the MC neuronal activity appears to code parameters of the motor output (Cheney and Fetz 1980; Evarts et al. 1983).

References

Boschert J, Hnik RF, Deecke L (1983) Finger movement versus toe movement-related potentials: further evidence for supplementary motor area (SMA) participation prior to voluntary action. Exp Brain Res 52: 73–80

Brinkman C, Porter R (1979) Supplementary motor area in the monkey. Activity of neurons during performance of a learned motor task. J Neurophysiol 42: 681–709

Chapman CE, Spidalieri C, Lamarre Y (1986) Activity of dentate neurons during arm movements triggered by visual, auditory, and somesthetic stimuli in the monkey. J Neurophysiol 55: 203–226

Cheney PD, Fetz EE (1980) Functional classes of primate corticomotoneuronal cells and their relation to active force. J Neurophysiol 44: 773–791

Deecke L, Kornhuber HH (1978) An electrical sign of participation of the mesial 'supplementary' motor cortex in human voluntary finger movement. Brain Res 159: 473–476

Eccles JC (1982) The initiation of voluntary movements by the supplementary motor area. Arch Psychiatr Nervenkr 231: 423–441

Evarts EV (1968) A technique for recording activity of subcortical neurons in moving animals. Electroenceph Clin Neurophysiol 24: 83–86

Evarts EV, Fromm C, Kroller J, Jennings VA (1983) Motor cortex control of finely graded forces. J Neurophysiol 49: 1199–1215

Evarts EV, Wise SP (1984) Basal ganglia outputs and motor control. In: Functions of the basal ganglia. Ciba Foundation Symposium 107. Pitman, London, pp 83–96

Godschalk M, Lemon RN, Kuypers HGJM, Ronday K (1984) Cortical afferents and efferents of monkey postarcuate area. An anatomical and electrophysiological study. Exp Brain Res 56: 420–424

Godschalk M, Lemon RN, Nijs HGT, Kuypers HGJM (1981) Behavior of neurons in monkey periarcuate and precentral cortex before and during visually guided arm and hand movements. Exp Brain Res 44: 113–116

Goldberg G (1985) Supplementary motor area structure and function: review and hypothesis. Behav Brain Sci 8: 567–615

Haider M, Groll-Knapp E, Gangberger JA (1981) Event-related slow (DC) potentials in the human brain. Rev Physiol Biochem Pharmacol 88: 125–197

Halsband U, Passingham R (1982) The role of premotor and parietal cortex in the direction of action. Brain Res 240: 368–372

Hashimoto S, Gemba H, Sasaki K (1981) Distribution of slow cortical potentials preceding self-paced hand and hindlimb movements in the premotor and motor areas of monkeys. Brain Res 224: 247–259

Humphrey DR (1979) On the cortical control of visually directed reaching: contributions by nonprecentral motor areas. In: Talbot RE, Humphrey DR (eds) Posture and movement. Raven, New York, pp 51–112

Ingvar DH, Philipson L (1977) Distribution of cerebral blood flow in the dominant hemisphere during motor ideation and motor performance. Ann Neurol 2: 230–237

Jürgens U (1984) The efferent and afferent connections of the supplementary motor area. Brain Res 300: 63–81

Kubota K, Hamada I (1978) Visual tracking and neuron activity in the post-arcuate area in monkeys. J Physiol Paris 74: 297–313

Kurata K, Okano K, Tanji J (1985) Distribution of neurons related to a hindlimb as opposed to forelimb movement in the monkey premotor cortex. Exp Brain Res 60: 188–191

Kurata K, Tanji J (1986) Premotor cortex neurons in macaques: activity before distal and proximal forelimb movements. J Neurosci 6: 403–411

Lamarre Y, Busby L, Spidalieri G (1983) Fast ballistic arm movements triggered by visual, auditory, and somesthetic stimuli in the monkey. I. Activity of precentral cortical neurons. J Neurophysiol 50: 1343–1358

Libet B, Wright EW, Gleason CA (1983) Preparation – or intention – to act, in relation to pre-event potentials recorded at the vertex. Electroenceph Clin Neurophysiol 56: 367–372

Marsden CD (1982) The mysterious motor function of the basal ganglia: the Robert Wartenberg lecture. Neurology 323: 524–539

Moll L, Kuypers HGJM (1977) Premotor cortical ablations in monkeys: contralateral changes in visually guided reaching behavior. Science 198: 317–319

Muakkasa KF, Strick PL (1979) Frontal lobe inputs to primate motor cortex: evidence for four somatotopically organized 'premotor' areas. Brain Res 177: 176–182

Murray EA, Coulter JB (1981) Organization of corticospinal neurones in the monkey. J Comp Neurol 195: 339–365

Okano K, Tanji J (1986) Comparison of triggered movement-related and self-paced movement-related neuronal activities in primate frontal motor fields. Neurosci Res Suppl 3: S89

Petrides M, Pandya DN (1984) Projections to the frontal cortex from the posterior parietal region in the rhesus monkey. J Comp Neurol 228: 105–116

Rizzolatti G, Matelli M, Pavesi G (1983) Deficits in attention and movement following the removal of postarcuate (area 6) and prearcuate (area 8) cortex in macaque monkeys. Brain 106: 655–673

Rizzolatti G, Scandolara C, Matelli M, Gentilucci M (1981) Afferent properties of periarcuate neurons in macaque monkeys. 2. Visual responses. Behav Brain Res 2: 147–163

Roland PE, Larsen B, Lassen NA, Skinhoj E (1980a) Supplementary motor area and other cortical areas in organization of voluntary movements in man. J Neurophysiol 43: 118–136

Roland PE, Skinhoj E, Lassen NA, Larsen B (1980) Different cortical areas in man in organization of voluntary movements in extrapersonal space. J Neurophysiol 43: 137–150

Sanides F (1964) The cuto-myeloarchitecture of the human frontal lobe and its relation to phylogenetic differentiation of the cerebral cortex. J Hirnforsch 6: 269–282

Schell GR, Strick PL (1984) The origin of thalamic inputs to the arcuate premotor and supplementary motor areas. J Neurosci 4: 539–560

Sessle BJ, Wiesendanger M (1982) Structural and functional definition of the motor cortex in the monkey (Macaca fascicularis). J Physiol (Lond) 323: 245–265

Talairach J, Bancaud J, Geier S, Bordas-Ferrer M, Bonis A, Szikla G, Rusu M (1973) The cingulate gyrus and behavior. Electroenceph Clin Neurophysiol 34: 45–52

Tanji J, Taniguchi K, Saga T (1980) Supplementary motor area: neuronal response to motor instructions. J Neurophysiol 43: 60–68

Tanji J, Kurata K (1982) Comparison of movement-related activity in two cortical motor areas of primates. J Neurophysiol 48: 633–653

Tanji J, Kurata K (1985) Contrasting neuronal activity in supplementary and precentral motor cortex of monkeys. I. Responses to instructions determining motor responses to forthcoming signals of different modalities. J Neurophysiol 53: 129–141

Weinrich M, Wise SP (1982) The premotor cortex of the monkey. J Neurosci 2: 1329–1345

Weinrich M, Wise SP, Mauritz K-M (1984) A neurophysiological study of the premotor cortex in the rhesus monkey. Brain 107: 385–414

Wiesendanger M (1981) Organization of secondary motor areas of cerebral cortex. In: Brooks (ed) Handbook of physiology. The nervous system, Vol II. Motor control. Am Physiol Soc, Washington, pp 1121–1147

Wiesendanger M (1986) Recent developments in studies of the supplementary motor area of primates. Rev Physiol Biochem Pharmacol 103: 1–59

Wiesendanger R, Wiesendanger M (1985) The thalamic connections with medial area 6 (supplementary motor cortex) in the monkey (Macaca fascicularis). Exp Brain Res 59: 91–104

Wise SP (1985) The primate premotor cortex: past, present and preparatory. Ann Rev Neurosci 8: 1–19

Wise SP, Mauritz K-H (1985) Set-related neuronal activity in the premotor cortex of rhesus monkeys: effects of changes in motor set. Proc R Soc Lond Biol 223: 331–354