bursts of multiple volleys, but here the last volley was always the largest. In nerve I of A_3 only single volley bursts were found. As with those in A_2, the bursts in A_3 characteristically ended abruptly and were followed by a small afterburst. It is important to note that the bursts in A_3 preceded the major volley in A_2 by 2 to 3 seconds (Fig. 2, D and E). This pattern serves to generate the peristaltic contractions that are observed in the intact animal.

The first hyperactive period that was provoked by application of hormone involved primarily rotational bursts. In the beginning, the bursts were relatively simple, consisting of one or two volleys. As the hyperactive period progressed, the complexity of the bursts increased, and those containing four or more volleys were not uncommon. The occurrence of rotational bursts continued into the quiet period. As in intact animals, activity during this second phase ranged from a decline in the frequency of bursts to a complete cessation of bursting. The appearance of the peristaltic pattern came with the onset of the third phase. Typically, this period was announced by a multivolley burst. Following this, the peristaltic bursts occurred at relatively constant intervals of 2 to 3 minutes. In occasional preparations, rotational bursts were mingled with those of the peristaltic type.

The response of deafferented preparations to the eclosion hormone clearly shows that the rotational and peristaltic movements arise from centrally generated motor patterns. Moreover, these patterns are parts of a central behavioral program that lasts approximately 1.5 hours and involves both the temporal arrangement of bursts and the progression from one burst type to the next. The information for repetitive oscillatory motor output (*10*) as well as rapid escape responses and postural changes (*11*) can be prepatterned in the nervous system. The pre-eclosion behavior differs from that in the above systems in that it involves a nonrepetitive sequence that lasts more than 1 hour and involves a number of distinct behavioral acts.

As with pheromones (*12*), the roles of hormones in behavior can be divided into two classes: "primers" and "releasers." Unlike pheromones, which are mainly releasers, hormones appear to serve typically a primer function; that is, the hormone alters the responsiveness of the nervous system so that a given set of stimuli evoke a new behavioral response. One such example in insects is the effect of juvenile hormone in promoting the maturation of adult reproductive behavior (*13*). A neurophysiological correlate of this type of primer function is seen in the action of various hormones on the level of spontaneous background activity in the insect central nervous system (*14, 15*). By contrast, the factor from the cockroach corpora cardiaca which causes a rhythmic bursting in the phallic nerve (*15*) serves as a releaser. The eclosion hormone serves a similar function in that it acts directly on the silk moth abdominal ganglia to release the appropriate prepatterned behavior.

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5. The term "pharate moth" refers to a moth prior to eclosion, that is, a moth which is still encased in the pupal cuticle [H. E. Hinton, *Nature* **157**, 552 (1946)]. For the present experiments it was important to have preparations that had not already been exposed to the eclosion hormone. To assure this, the moths emerging on a given day (as evidenced by the full resorption of the molting fluid) were decapitated just before the lights were turned on. [In the photoperiod (LD 17 : 7) to which the cecropia were exposed, the brain releases the eclosion hormone shortly after the lights are turned on.] For the remainder of the day, the abdomens were taken from the decapitated animals as needed.
6. A needle was inserted into the lumen and the abdomen was thoroughly washed out with 15 ml of cold Weevers solution [R. deG. Weevers, *J. Exp. Biol.* **44**, 163 (1966)]. During this procedure, we removed the gonads, gut, rectal sac, and as many of the Malpighian tubules as possible.
7. In the earlier preparations, the nerves to the genitalia from A_4 were left intact because of their intimate association with the trachea. The presence or absence of this innervation proved to be inconsequential.
8. Tape records of nerve activity were played back through a pair of window discriminators which were set to trigger on all spikes regardless of amplitude. The resulting trains of uniform pulses were then led to a pair of simple RC integrators (time constant, 0.1 second), and the integrated output of each data track was recorded on separate penwriter channels of a Grass polygraph.
9. The eclosion hormone was prepared from the brains and corpora cardiaca of two pharate moths. The organs were homogenized with 40 μl of Weevers solution in a ground-glass homogenizer. The entire homogenate was routinely added to the preparation at the onset of recording.
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Human Motor Cortex: Sensory Input Data from Single Neuron Recordings

Abstract. *Recordings were made from single neurons in the hand area of the human motor cortex while peripheral physiologic stimuli were applied. Such cells responded only to active and passive hand movements. Tactile and auditory (click) stimuli were ineffective. The majority of cells were activated only by movements of the contralateral hand, but a significant number (4 of 16) could be excited if a given movement was made by either hand. Of the cells responding to active movement, some showed an increased discharge before onset of the voluntary action. Such cells were excited by the same movement executed passively, a result that indicates sensory feedback from receptors activated by that movement.*

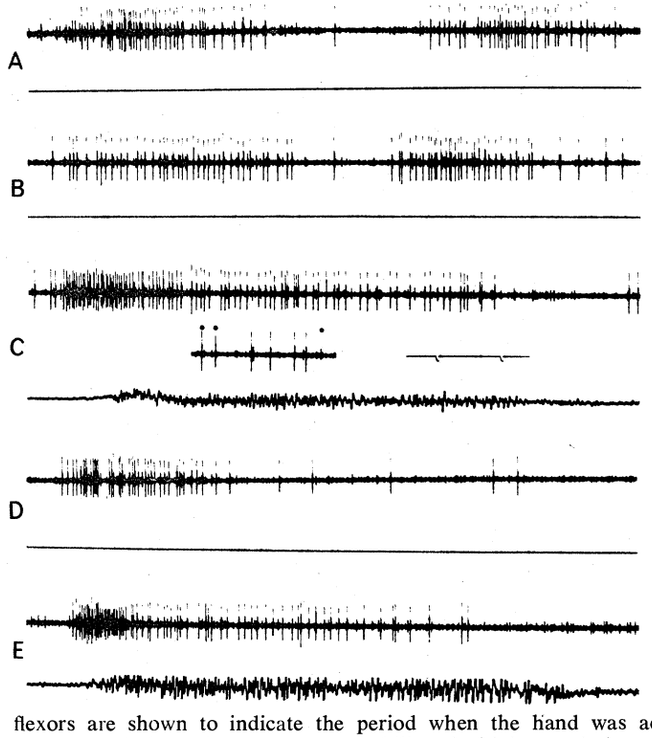
In a study of sensory input to the motor cortex (*1*), human subjects showed responses in the motor hand area which were evoked by electrical stimulation of the contralateral median nerve (MN). Stimulation of the ipsilateral MN and auditory (click) stimulation, both of which elicited responses in cat and squirrel monkey, were ineffective in man. Those observations suggested that the human motor cortex, compared with the homologous animal

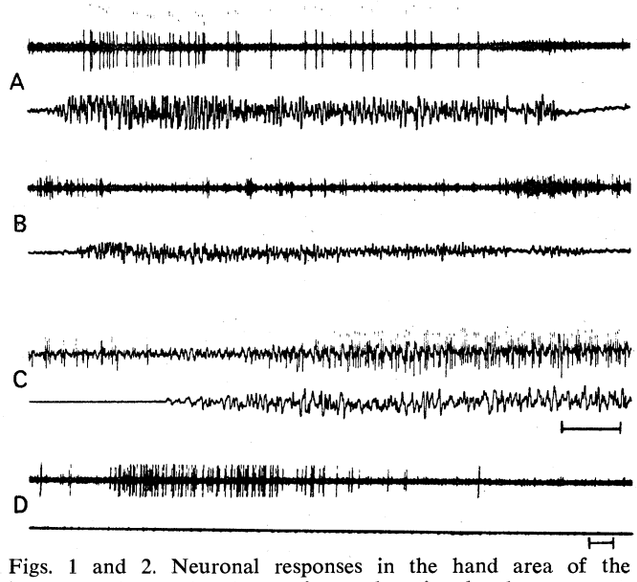
cortex, was less concerned with integration of diverse sensory inputs from the periphery. To further characterize the sensory input to the human motor cortex, this study was extended to include recordings of responses of single cells to physiologic stimuli.

With the use of platinum-iridium microelectrodes coated with glass (*2*), extracellular records were made from 30 cells of the motor hand area in five subjects during craniotomy for focal epilepsy. Surgery was carried out under local anesthesia with the patient awake, and in each subject records were made from that area of the motor cortex in which electrical stimulation elicited a predominantly flexor hand movement. Each cell was studied incident to active closing and opening of the hand (executed in response to the commands "close" and "open"), to passive flexion and extension of the digits and wrist (each carried out independently), to tactile stimulation (with a cotton wisp), and to electronically generated clicks. The electromyograms of the flexors and extensors of the hand were recorded with disk electrodes on the forearm surface, simultaneously with recordings of activity of the cortical cells. A Grass high-impedance probe and P 511 differential amplifier, linked with both oscilloscope and tape recorder via a variable band-pass filter (low- and high-frequency cutoff between 500 and 2000 hz) were used to record unit activity. Permanent records for photography were subsequently retrieved from the taped records with an Oscillomink liquid jet recorder.

In none of the five subjects did the focal epileptogenic lesion include the motor cortex. Electrode penetrations were made in avascular areas, and recording time was limited to 1 hour. The observations were carried out in full accord with the U.S. Public Health Service policies governing human investigations, and there were no untoward effects from the microelectrode penetrations.

Of the 30 cells tested, 16 were responsive; the remainder did not respond to any of the stimuli. Before recording from single units, we made computer-averaged records of responses to electrical stimulation of the contralateral and ipsilateral MN. Only contralateral stimulation evoked a response; ipsilateral stimulation had no significant effect, in agreement with our earlier observations (*1*). By contrast, 4 of the 16 responding cells (each from a different subject) responded to both ipsilateral and contralateral physiologic stimulation. Two were activated by passive flexion of the fingers (Fig. 1, A and B), and two by passive wrist flexion. The opposite movement (extension) suppressed the spontaneous discharge in all four neurons. These bilaterally





Figs. 1 and 2. Neuronal responses in the hand area of the human motor cortex to passive and active hand movement. The top trace of each pair is the cortical unit activity; the bottom one is the electromyogram of the contralateral hand and finger flexors, monitored in the forearm. Records were made from both flexors and extensors, but only records from flexors are shown to indicate the period when the hand was actively closed and opened. With these movements, both flexors and extensors of the wrist contract to stabilize that joint, and thus activity from either muscle group reflects the period of movement. Fig. 1 (left). All records are from the same cortical units. (A) Responses to two passive flexions of contralateral fingers are shown. (B) Responses to two similar passive flexions of ipsilateral fingers are seen. (C) Responses to active closure of the contralateral hand are shown. Note onset of cortical unit discharge before the appearance of muscle activity. Suppression of firing when the hand was opened (at the end of trace) was consistently seen. The inset trace in C is spontaneous activity; three separate units are each identified by a dot. (D) Responses to active closing and opening of the ipsilateral hand are seen. Note absence of any muscle activity in the electromyogram from the contralateral hand; this absence excludes the possibility that the cortical unit response reflects involuntary movement of the contralateral hand during closing and opening of the ipsilateral hand. (E) Responses to active closing and opening of both hands are seen. The latency between cortical unit response and appearance of muscle activity is less than that which occurs with contralateral closure alone (C). During periods when the subject was actively closing and opening his hand, he never achieved complete muscle relaxation in the interval between the completion of hand-opening and the beginning of the next hand-closing. This accounts for the difference between the electromyogram baselines for passive (A and B) and active (C and E) movements. The time scale is 1 second. Fig. 2 (right). Records in A and B are from two different units in the same subject; records in C and D are from two other subjects. The cortical record in C is unfiltered. The time scales are 1 second; the upper applies to A, B, and C, and the lower to D.

activated cells were found in both dominant and nondominant hemispheres, and none of the subjects in whom they were encountered was ambidextrous.

The cell that responded to passive finger flexion (Fig. 1, A and B) also responded to active closing and opening of the hand. When the subject actively closed his hand (Fig. 1C), cell discharge increased before onset of movement, and the increased firing continued during sustained closure (*3*). Opening the hand elicited the opposite response; cell discharge was completely suppressed for 1 to 2 seconds. Ipsilateral movement was as effective as contralateral, although the response adapted more quickly during sustained closure of the ipsilateral hand than during that of the contralateral (Fig. 1D). When the subject was instructed to close both hands, the latency between unit discharge and muscle activity was decreased (Fig. 1E). Thus, this cell, which could be involved in the initiation of finger flexion, as evidenced by the cell discharge that preceded the onset of voluntary hand closure (*4*), receives sensory feedback from the receptors activated by that movement, as shown by the cell's response to passive flexion of the digits. Such an input-output linkage is reminiscent of observations in animals, in which microstimulation of single pyramidal cortical cell or a few such cells produces movement in limb regions that have receptors that project to these same cells (*5–7*).

Only passive or active movement influenced the 16 responsive cells; none of the cells responded to tactile stimulation (*8*) or to click as do cells in the motor cortex of the cat (*9*). In that animal 60 percent of the responding cells are tactually activated (*9*). In the macaque the situation is more closely akin to that in man. The input there is predominantly kinesthetic (*7, 10*), but approximately 8 percent of the cells do respond to tactile stimulation (*6*).

Patterns of response other than that shown in Fig. 1 were as follows. Four cells discharged during sustained closure of the contralateral hand (Fig. 2A). In four cells, discharge was suppressed during sustained closure of the contralateral hand (Fig. 2B). In two cells, suppression of firing preceded voluntary closure of the contralateral or ipsilateral hand and was followed by increased discharge during sustained closure (Fig. 2C); passive finger flexion of either hand also evoked an increased discharge. In two cells, firing increased in response to passive flexion of the contralateral digits, passive extension of these digits suppressing cell discharge (Fig. 2D).

In Fig. 2, A, B, and D, are examples of responses of cells with a local receptive field (that is, input from the contralateral hand only). The only cells found to have a more extensive receptive field are those with bilateral input from the hands (Fig. 1, A and B). Cells with input from lower as well as upper extremities have been found in the motor cortex in both cat (*11*) and macaque (*7*), but have not been seen in man.

With the electrode penetration used to obtain the records in Fig. 1, activity from more than one cell was recorded. This was true with most of the electrode penetrations. The inset trace in Fig. 1C is a record of spontaneous activity and shows three different neurons, which can be distinguished by their different firing amplitudes, the amplitude indicating the cell's proximity to the recording electrode. In Fig. 1C the two larger neurons both respond to active closure and opening of the hand, while the smaller and more distant cell is unaffected by this movement. This is especially evident when the hand is opened, a movement that results in suppression of activity of the two larger units but not of the smaller one. Another clear example of neighboring cells that exhibit an identical function is evident in Fig. 2D; there both the smaller and larger units respond to passive flexion. Whether or not cells in the human motor cortex are functionally organized in radial columns, as is the case in animals (*11*), we cannot say. However, it does appear that cells that are in very close proximity to one another function similarly.

Although the number of cells studied is relatively small, the fact that 4 of the 16 responsive cells showed a bilateral input indicates that there is a significant ipsilateral projection to the motor hand area in the human, similar to that found in animals (*9*). Nevertheless, the other aspects of neuronal response to physiologic stimuli indicate important differences between man and animals, since the sensory projection to the motor hand area of the human is proving to be exclusively a kinesthetic (*12, 13*) one and to be derived only from the hands. Thus we continue to view the human motor cortex as a highly specialized region that functions more like a "final common path determiner of movement" (*1*). It appears that, in man, the function of processing diverse sensory inputs from the periphery, a function characterizing the motor cortex of the cat and, to a lesser extent, that of the macaque, has been relegated elsewhere.

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