18. A. Kling, personal observation.
19. Four rhesus monkeys were treated in a previous study with 300 mg/kg per day for 1 year, with no reported behavioral effects or toxicity, in an attempt to produce cataracts [E. J. Gralla and L. Rubin, *Arch. Ophthalmol.* **83**, 734 (1970)]. Another study of sleep patterns in monkeys reported no changes during the waking period after single doses of 330 to 1000 mg/kg [E. D. Weitzman *et al.* (*6*)]. Hair loss has been reported in rats [Shillito (*9*)] and paresthesias have been described in humans [Cremata and Koe (*13*)].
20. This is similar to the sexual effects described in humans [W. T. Carpenter, Jr., in A. Sjoerdsma *et al.* (*6*)] and contrary to that seen in rats, rabbits, and cats (*8, 9*).
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Operant Conditioning of Specific Patterns of Neural and Muscular Activity

Abstract. *In awake monkeys we recorded activity of single "motor" cortex cells, four contralateral arm muscles, and elbow position, while operantly reinforcing several patterns of motor activity. With the monkey's arm held semiprone in a cast hinged at the elbow, we reinforced active elbow movements and tested cell responses to passive elbow movements. With the cast immobilized we reinforced isometric contraction of each of the four muscles in isolation, and bursts of cortical cell activity with and without simultaneous suppression of muscle activity. Correlations between a precentral cell and specific arm muscles consistently appeared under several behavioral conditions, but could be dissociated by reinforcing cell activity and muscle suppression.*

In investigating the possible role of precentral "motor" cortex cells in generating voluntary movements, previous experimenters trained monkeys to perform specific motor responses by making operant reinforcement contingent on the position and force trajectories of the responding limb (*1, 2*). Such response patterns involved coordinated activity of many muscles of the responding limb (*2, 3*) and therefore were not designed to resolve the question of which specific muscles a given cortical cell may influence. To determine the degree to which precentral cell activity may be correlated with specific limb muscles and to test the stability of such correlations during different behaviors, we recorded the activity of single precentral cells and four major arm muscles (a flexor and extensor of wrist and elbow) while reinforcing specific patterns of activity in these elements.

Experiments were performed with a fluid-deprived monkey (*Macaca mulatta*) seated in a restraint chair with his head immobilized and a juice-dispensing tube in his mouth. The monkey's arm could be held semiprone in a molded cast pivoted at the elbow, allowing measurable flexion and extension of the elbow but no gross movement of the wrist. The cast could also be locked in place (elbow at 90°, wrist at 180°), rendering all muscle contractions isometric (*4*). Electromyographic (EMG) activity of major flexors and extensors of the wrist (flexor carpi radialis and extensor carpi radialis) and elbow (biceps and triceps) was recorded through pairs of braided stainless steel wires permanently implanted in the belly of each muscle and led subcutaneously to a connector implanted on the skull. Activity of single precentral cells in contralateral cortex was recorded with tungsten microelectrodes. For about a month prior to the data-recording sessions, the monkey was trained in several behavior performances: (i) He was reinforced with fruit juice for sitting quietly while we tested the cells' responses to passive movement of the arm and cutaneous stimulation. (ii) With his arm in the position monitor he was reinforced for active flexion and extension of the elbow. (iii) With the position monitor locked in place, reinforcement was made contingent upon isometric contraction of any one of the muscles with simultaneous suppression of activity in the other three.

Specific patterns of cell and muscle activity were monitored and reinforced with an electronic "activity integrator" which continuously integrated a weighted sum of voltages proportional to cortical cell and muscle activity, and delivered a reinforcement when the resultant voltage exceeded a preset threshold (Fig. 1). The activity integrator had several input channels which accepted either voltage pulses triggered from the cell's action potentials or rectified EMG activity from specific muscles. A summing network produced a weighted sum

$$V(t) = \sum_i a_i v_i(t)$$

of these input voltages; the algebraic sign and magnitude of each weighting factor a_i were determined by the experimenter through a polarity switch and gain control for each channel. This summed voltage was temporally integrated with a parallel resistor-capacitor network with a time constant of 50 to 100 msec to generate the "integrator voltage." When this integrator voltage reached a preset threshold level V_T the feeder discharged and the integrator voltage was briefly reset to zero.

To illustrate a typical application, consider reinforcing the activity of a specific muscle, say biceps, in isolation. When cortical unit activity did not enter into the reinforcement contingency, its contribution to the integrator voltage was switched off ($a_5 = 0$). The polarity switches that were on the muscle channels were set such that activity in the biceps drove the integrator voltage toward threshold ($a_3 > 0$), while activity in the other three muscles drove the voltage away from threshold ($\alpha_i < 0$; $i = 1,2,4$). When reinforcement became available, the monkey typically began to emit bursts of EMG activity in several arm muscles every few seconds. The gain controls (a_i) were set such that approximately half of these burst responses were reinforced. After sev-

eral minutes the proportion of reinforced responses typically increased. By reducing the gain on the biceps channel we could require the monkey to produce more biceps activity to reach threshold; by increasing the gains on the other muscle channels we could require a greater suppression of activity in these muscles in order to prevent reinforcement from being withheld. Thus, separation of activity in different muscles was accomplished by selectively reinforcing better successive approximations to the required pattern. Terminal performance typically consisted of repeated bursts of EMG activity in the reinforced muscle with negligible coactivation of the other three muscles.

During reinforcement periods a meter in front of the monkey was illuminated and its needle deflection was made proportional to the integrator voltage. Extreme rightward deflections were consistently correlated with juice reinforcement; thus the meter deflections could become a conditioned reinforcer. During reinforcement of isolated activity of specific muscles a set of colored lights indicated which muscle was being reinforced, and the amplified EMG activity of the reinforced muscle was audible to the monkey (*5*).

The results from one 8-hour experiment are presented in detail to illustrate the relation between a precentral cell and major flexors and extensors of elbow and wrist during passive and active elbow movements (Fig. 2) and under isometric conditions while reinforcing isolated muscle activity or cortical unit activity (Fig. 3).

Passive movements of the contralateral elbow and wrist reliably evoked responses from this cell, but cutaneous stimulation (brushing hairs or touching skin) did not. The cell responded repeatedly to passive extension of the elbow (Fig. 2B) and to passive flexion of the wrist without overt signs of resistance or gross EMG activity (*6*). When *active* movements of the elbow were reinforced, the cell invariably fired in relation to active flexion (Fig. 2A). Flexion was also accompanied by activity in both wrist muscles as well as biceps, but the bell-shaped average of cell activity more closely resembled that of biceps than the averages of either wrist muscle. The peak discharge frequency of the cell occurred approximately 100 msec before peak activity of the biceps (*7*).

With the monkey's arm cast locked in place and with appropriate discriminative stimuli, we reinforced the monkey for isometric contractions of a particular muscle when accompanied by concomitant suppression of activity in the three remaining muscles. After a brief practice period, such differential reinforcement resulted in repeated bursts of activity predominantly or exclusively in the reinforced muscle. Selective reinforcement of isolated activity in flexor carpi radialis resulted in bursts of activity in that muscle without appreciable cocontraction of the other three muscles (Fig. 3A). Some cell activity accompanied the wrist flexor bursts, but this was more variable and less intense than that accompanying biceps bursts. Bursts of extensor carpi radialis activity were difficult to obtain without some concurrent activity in the wrist flexor (Fig. 3B). However, negligible cell activity accompanied this pattern of wrist muscle activity. Isolated bursts of biceps activity were emitted with minimal cocontraction of wrist muscles or triceps (Fig. 3C). In this case the cell began to fire well in advance of the biceps activity and reached its peak frequency coincident with the maximum muscle activity. Reinforcing isolated triceps activity resulted in sharp bursts of activity in this muscle with some coactivation of both wrist muscles (Fig. 3D). Relatively little cell activity accompanied this pattern. Analysis of the relationships between the precentral cell activity and isometric contraction of the four arm muscles suggests that the activity of this cell was most strongly correlated with contraction of the biceps muscle.

Next, with his arm still immobilized in the cast, the monkey was reinforced for bursts of cortical cell activity with no contingency imposed on the EMG activity. Under these conditions bursts of cell activity were repeatedly accompanied by bursts of EMG activity in the biceps and both wrist muscles (Fig. 3E). The amount of EMG activity accompanying successive unit bursts fluctuated by a small amount, but some degree of muscle activity was invari-

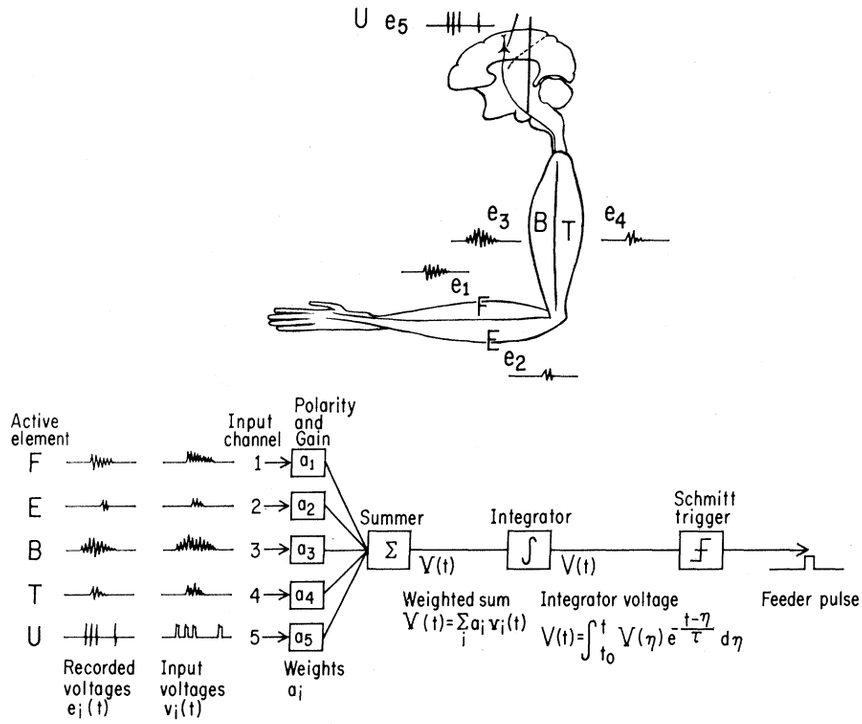

Fig. 1. (Top) Schematic diagram of monkey, showing location of arm muscles and precentral cell, with typical recorded potentials (e_i). *F*, flexor carpi radialis; *E*, extensor carpi radialis; *B*, biceps; *T*, triceps; *U*, precentral cell. (Bottom) Schematic of "activity integrator" used to reinforce patterns of activity under isometric conditions. Input voltages (v_i) were rectified EMG activity for muscles or voltage pulses triggered from the cell's action potentials. The weighted sum was temporally integrated in a parallel resistance-capacitance network; when the integrator voltage reached the Schmitt trigger threshold, the feeder discharged and a relay (not shown) briefly reset the integrator voltage to zero.

ably associated with each burst of cell activity. The previously observed correlation between cell and biceps activity was again apparent, with peak cell activity preceding peak biceps activity by 70 msec.

We then attempted to dissociate the correlation between cell and muscle activity by reinforcing bursts of cell activity with simultaneous suppression of all muscle activity (*8*). After approximately 15 minutes of reinforcing successively better approximations to the required pattern—involving about 100 reinforced response patterns and an equal number of unreinforced responses—the monkey repeatedly emitted bursts of cortical cell activity without any measurable EMG activity (Fig. 3F).

The reverse dissociation of cell and biceps activity was attempted next by reinforcing isometric biceps activity accompanied by simultaneous suppression of cortical cell activity. This schedule was imposed after 7 hours of conditioning, involving some 3000 reinforcements, and the monkey's rate of responding was clearly decreasing. In 25 minutes of reinforcing the closest approximations to the required pattern, the monkey emitted about 200 reinforced responses and about 60 unreinforced patterns. At the end of this period the response patterns consisted of intense biceps bursts, with some remaining concomitant cell activity, as well as wrist muscle activity. Averages of unit and muscle activity over the last 50 reinforced responses, computed at the same gains as the averages for reinforced unit bursts (Fig. 3G), show a 300 percent increase in area under the biceps average and a 10 percent decrease in average cell activity, indicating a net change in the reinforced direction. Failure to achieve total suppression of cell activity during biceps bursts on this schedule may reflect fatigue or satiation (*9*).

Of a large number of precentral cells observed, 16 have been studied under at least half of the above conditions (not counting unit suppression with muscle activation, which was only documented for the illustrated cell) (*10*). Of the nine precentral cells (six pyramidal tract cells) observed in relation to isometric contraction of each of the four arm muscles, three cells were predominantly related to only one or two muscles, two were not strongly related to any, and four fired in relation to all four muscles (two of these exhibited the same pattern in relation to all four muscles). Relations to antagonistic muscles were more often the same (six cases) or not comparable (five) than reciprocal (three). Unit-muscle correlations seen in the isometric case were usually, but not always, consistent with those seen during active movements.

The ease with which the monkey suppressed muscle activity previously associated with precentral cell activity led us to attempt similar dissociation with five other cells. In each case (i) the cell fired repeatedly before a specific muscle or group of muscles during active elbow movements, or isometric contraction, or both; (ii) reinforcing bursts of activity of that cell, with no contingency on muscle activity, produced unit bursts accompanied by contraction in those same muscles and often in other muscles as well; and (iii) selective reinforcement of bursts of cell activity with simultaneous suppression of muscle activity resulted in substantial or total (80 to 100 percent) suppression of EMG activity with little or no decrease in the intensity of unit bursts.

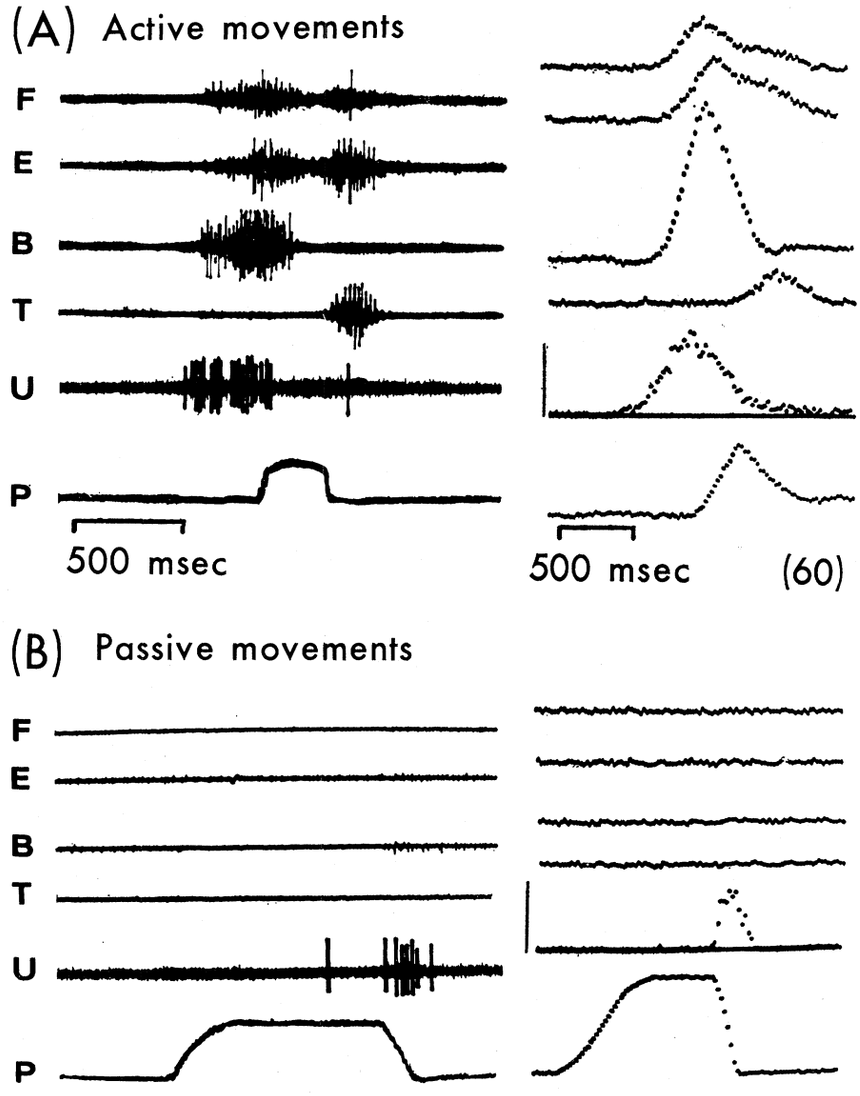

Fig. 2. Responses of precentral cell and arm muscles during active and passive elbow movements. Successive lines from top to bottom show activity of flexor carpi radialis (*F*), extensor carpi radialis (*E*), biceps (*B*), triceps (*T*), cortical unit (*U*), and the position of the elbow (*P*). A single trial is shown at left, and the averages over 60 successive trials at right. This cell fired before active flexion of the elbow (A) and responded to passive extension of the elbow (B). All EMG averages were computed at identical gains. Time histogram of cell activity is shown with a zero baseline; vertical calibration bar equals 50 impulses per second. Upward deflection of the position monitor represents flexion.

These observations would suggest some caution in interpreting temporal correlations as final evidence for functional relations. A consistent temporal correlation between two events, such as precentral cell activity and some component of the motor response (force, position, or activity of a specific muscle) is necessary but never sufficient evidence for a causal relation between the correlated events. The evidence can be strengthened by demonstrating that the correlation persists while other aspects of the response pattern are varied. In the present example, activity of the illustrated cell was consistently associated with activity of biceps (and to a lesser extent with flexor carpi radialis) whether we reinforced active elbow flexion, isolated muscle contraction, or bursts of cortical cell activity. Such a consistent temporal correlation under a variety of behavioral conditions would seem to be strong evidence for a functional relation. When cell and muscle activity were simultaneously included in the reinforcement contingency, however, we found that the correlated muscle activity could readily be suppressed. These observations sug-

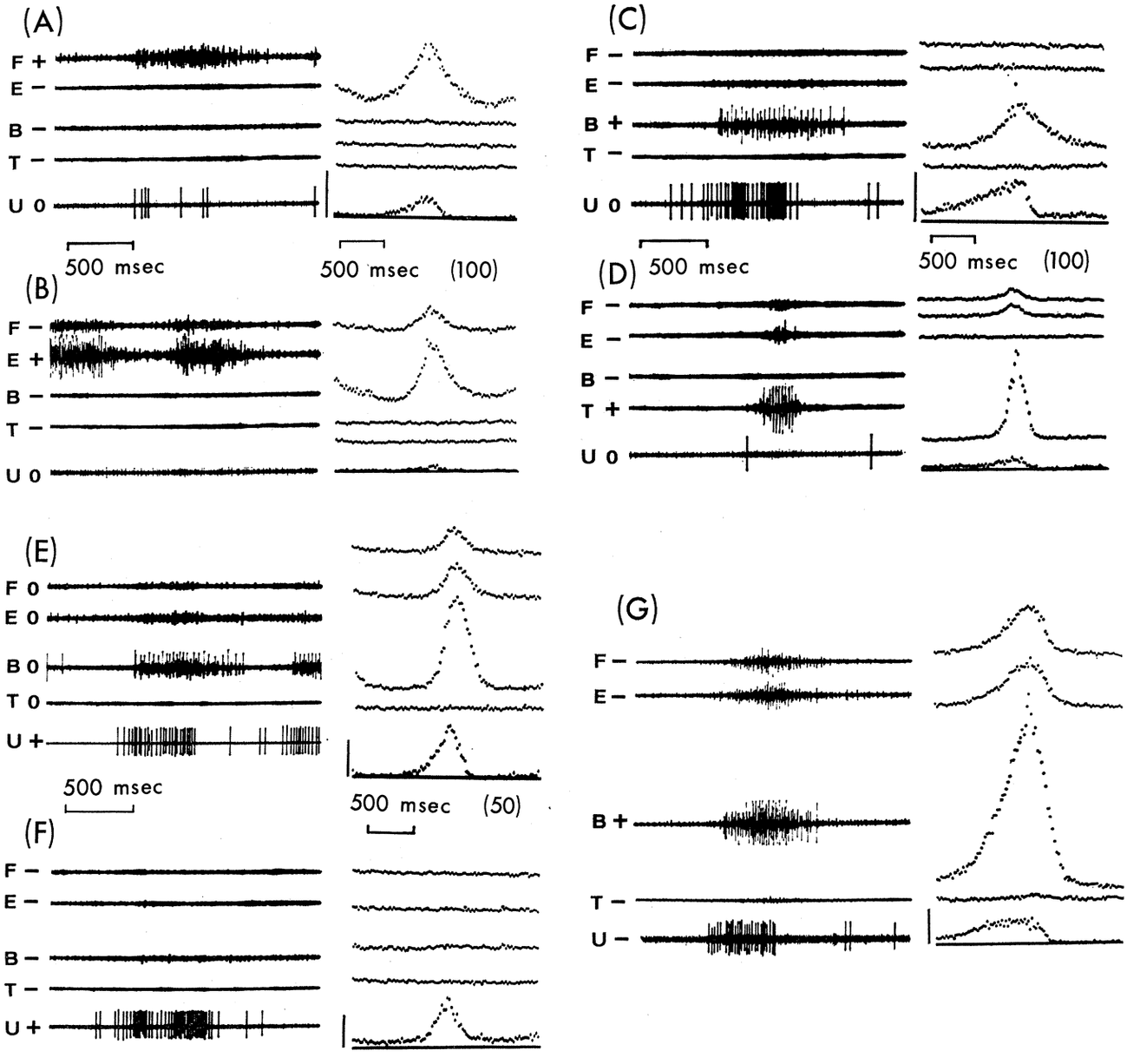

Fig. 3. Operant reinforcement of patterns of neural and muscular activity under isometric condition. (The labels of the horizontal lines are as in Fig. 2.) Muscles and unit are labeled "+" or "−" to indicate whether their activity drove the integrator voltage toward (+) or away (−) from threshold, or with a "0" if their activity was not included in the reinforcement contingency. For (A) to (D) the monkey was reinforced for isometric contractions of each specific muscle in isolation: flexor carpi radialis (A), extensor carpi radialis (B), biceps (C), and triceps (D). Averages for (A) to (D) were computed for 100 responses, with the vertical scale of all EMG averages identical except for a reduction of (D) by one half. In (E) and (F) the monkey was reinforced for bursts of cortical cell activity, first with no contingency on the muscles (E), then requiring simultaneous suppression of all muscle activity (F). In (G) biceps activity and unit suppression were reinforced. Averages for (E) to (G) were computed for 50 successive responses, with identical vertical scale on EMG averages. Vertical bars on time histograms of unity activity represent 50 impulses per second; the scale for (B) and (D) is the same as (C).

gest that a possible test of the stability of an observed temporal correlation would be operant reinforcement of its dissociation (*11*).

On the other hand, successful dissociation does not disprove a possible functional relation between the precentral cell and muscles; it merely demonstrates the flexibility of that relation. As others have already noted, the activity of single precentral cells (*1, 2*) or specific motor units (*12*) may be quite variably related to similar force or position trajectories in successive motor responses. To what extent our EMG recordings are representative of the activity of these and synergistic muscles remains to be documented. These preliminary results suggest that a useful approach to investigating relationships between central cells and muscles is to study the activity of the same elements under as many different behavioral conditions as possible, including operant reinforcement of specific response patterns.

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4. Under isometric conditions integrated EMG activity has been demonstrated to be proportional to muscle tension [V. T. Inman *et al., Electroencephalogr. Clin. Neurophysiol.* **4**, 187 (1952); O. C. J. Lippold, *J. Physiol.* **117**, 492 (1952); B. Bigland and O. C. J. Lippold, *ibid.* **123**, 214 (1954)].
5. A seven-channel FM tape system recorded the activity of the precentral cell and four arm muscles, the position of the elbow during passive and active movements, and a delayed trigger pulse 1 second after the occurrence of each reinforced response pattern. Playing the tape backward, we used these delayed pulses to trigger a Nuclear-Chicago Data Retrieval Computer, which computed averages of the full-wave rectified EMG activity of each muscle and time histograms of unit activity over 2-second intervals around the reinforced responses.
6. A small, brief EMG response of biceps during passive elbow extension, seen on close inspection of single trials, was probably due to the myotatic stretch reflex; this response was not large enough to appear on the averages at the same gain used for active movements.
7. Active elbow extension was accompanied by some triceps activity, but due to unequal loading, required somewhat less force than active flexion. Note that cell activity accompanying *active* extension was negligible compared to the response evoked by comparable rates of *passive* extension.
8. While voltage pulses triggered by the cell's action potentials drove the integrator voltage toward reinforcement threshold, activity of any muscles drove the integrator voltage away from threshold. The relative contribution of the EMG activity was minimized initially so that only those unit bursts accompanied by lesser amounts of EMG activity were reinforced. As the monkey emitted less EMG activity with successive unit bursts the gains on the EMG channels were gradually increased to require further EMG suppression for reinforcement.
9. After a rest period, however, the monkey still performed the active flexions and extensions of the elbow. The actual sequence of the described observations was: passive movements of elbow and wrist; isometric contraction of biceps, triceps, extensor carpi radialis, flexor carpi radialis; reinforced unit bursts; unit bursts with EMG suppression; biceps bursts with unit suppression; passive elbow movements; active elbow movements.
10. Eight of these cells were identified as pyramidal tract (PT) cells on the basis of an invariant antidromic response to stimulation of the medullary pyramids. Three cells did not respond to PT stimulation, and five cells, including the one illustrated, were studied before the pyramidal tract electrode was implanted.
11. By showing that specific components of the visual evoked response may be altered by operant reinforcement, S. S. Fox and A. P. Rudell [*J. Neurophysiol.* **33**, 548 (1970)] demonstrated that consistent correlations between neural responses in a sensory system and the evoking stimulus may be operantly dissociated.
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Redwoods: A Population Model Debunked

In his article Bosch (*1*) gives license to lumber companies to harvest 50 percent of all redwoods under 800 years old, claiming that the trees would still "survive and flourish." He states that "there is a trade-off between a model so complex as to defy analysis and one so simple that no real conclusions can be drawn from it." His model for *Sequoia sempervirens* forests falls in the latter class; its deficiencies must be made known because of the possible danger that someone might take his recommendations seriously.

To begin with, the concepts of population biology employed are faulty. The redwood "belt" of central and northern California actually consists of a series of disjunct populations, each subjected to somewhat different environmental conditions. For example, in central California *Sequoia sempervirens* forms nearly pure stands in deeper canyons and ravines, but it is associated with Douglas fir (*Pseudotsuga menziesii*) in drier areas (*2*). That the age distribution, seed set, and survival are identical or even comparable between these two habitats is unlikely. Moreover, it is even more unlikely that these characteristics are the same for the Big Sur population as they are for populations in Humboldt County. To make a model for "the redwoods" based on data from one virgin stand in one locality is at best naive.

Furthermore, the application of a model based on data from an undisturbed stand to predict the effects of harvesting is unlikely to produce conclusions even vaguely approaching reality. The redwoods are often logged by clear-cutting. By no stretch of the imagination can the combination of 500 acres of virgin forest and 500 acres of clear-cut forest be expected to have the same population dynamics as a 1000-acre stand logged very carefully by selective cutting. Indeed, even a selectively cut stand should not be expected to replace its losses at rates comparable to those of an intact stand.

Finally, the model is not even appropriate to describe the dynamics of one virgin stand in Humboldt County. This model uses fecundity and survival values inappropriate even for the intact stand, much less for a logged area. For example, the assumption is made that, in each 50-year period, 18 percent of the class 2 trees (ages 200 to 800 years) will go on to class 3 (800 years and up), and that 92 percent will remain in class 2. Without even an allowance for deaths, this has accounted for 110 percent of the class 2 trees.

More crucial, the estimate that, in each 50-year period, 30 percent of the class 1 trees will graduate to class 2 is five to ten times the correct value. The numbers of individuals in each age class in a population are a function of both advancement from the previous class and deaths occurring within the new class. This is very critical, because the overstatement of survivorship is exactly what leads to the erroneous conclusions. Since no more than 10 percent of the class 1 trees are going to be between 150 and 200 years (accord-