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DORSAL RHIZOTOMY IN RHESUS MONKEYS:
REACHING WITHOUT VISUAL GUIDANCE

BY

GIL C. ALLEN

A dissertation submitted to the Graduate
Faculty in Psychology in partial fulfill-
ment of the requirements for the degree
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Supervisory Committee

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CHAPTER I

INTRODUCTION

Nature of the Problem

For many years, researchers have attempted to ascertain the degree to which proprioception is essential to the performance of purposive movements in monkeys. Proprioceptive input, as well as other somatosensory input, can be eliminated from a limb by deafferentation, here defined as the surgical section of dorsal roots at the spinal cord. After this is done, a remarkable amount of recovery of motor function occurs when certain specific postoperative caring procedures (described by Bossom, 1972, 1974; Taub, Perrela, & Barro, 1973) and training techniques (reviewed by Taub & Berman, 1968) are utilized.

Emphasis has been placed on exteroceptive and central feedback factors to account for the motor performance of deafferented monkeys (deafferents). Vision has been shown to be one important exteroceptive feedback source in that it can substitute for proprioceptive feedback in the postoperative development of reaching behavior in deafferents (Gianutsos, unpublished dissertation, 1975; Gianutsos & Berman, 1975; Taub, E., Goldberg, & Taub, P., 1975). Deafferents provided with visual guidance during shaping to reach several targets could reach the same targets presented in irregular order and without visual guidance. (Taub, et al., 1975). It is possible that the observations of Taub, et al. resulted from the fact that visual guidance was available during shaping. It can be argued that the presence of visual guidance during shaping permitted the laying down of "memory traces" which the deafferent may have utilized when visual guidance was not available during testing. The purpose of this research was to explore whether monkeys can use their deafferented limb to perform movements to targets presented in random order when visual guidance is excluded during shaping and testing.

Behavioral and Neurological Effects of Deafferentation

One of the first experiments to test the behavioral effects of deafferentation was reported by Mott and Sherrington in 1895. They found that, in the free situation, unilaterally deafferented (C4-T4) monkeys did not use their deafferented limbs to ambulate, reach for food or grasp objects, although occasional random flexions and extensions of the limb did occur. Movements of the shoulder showed less impairment than those at the elbow, and the greatest deficits were noticed with prehensile movements. They concluded that somatic sensation was necessary for purposive movements. The deficits described by Mott and Sherrington were greater than those seen after motor cortex ablations, or those described later by Lassek for parietal cortex ablations (1955) or section of the posterior columns (1954).

More recent studies have confirmed these earlier findings. In a study with Denny-Brown, Sherrington (1931) confirmed his earlier findings with Mott. Again, unilaterally deafferented (C5-T3) monkeys showed an almost complete inability to make use of the affected limb. Furthermore, when the motor cortex was electrically stimulated, deafferented and intact limbs showed the same degree of muscle movement and coordination, quite different from the wild flailing and completely uncoordinated movements of the deafferented limb in the free situation.

Lassek (1953a) reported that unilaterally deafferented (C2-T4) limbs of monkeys showed severe impairment, resembling a flaccid paralysis where the arm had little tone, fell, "as a dead weight when released from an elevated position" and swung "pendulously back and forth" (p. 84) in a free roaming situation. The affected arm was not employed in any postural or skilled movements, such as grasping, climbing, eating or supporting the animal in a sitting position. Biceps and triceps tendon reflexes as well as grasp reflex could not be elicited, although the scratch reflex remained intact.

Twitchell (1954) noted that monkeys with one forelimb deafferented (C3-T3) showed sporadic flexion and extension movements at the elbow and shoulder. Contrary to Lassek's (1953a) findings, Twitchell's animals kept the deafferented arm slightly flexed, not flaccid, and it remained in this position when the animal was walking. Twitchell also noticed that the animals defended themselves using the deafferented limb provided they could see the threatening object. Once blindfolded, however, they did not use the deafferented limb for defense. He reasoned that the animals learned to use the tonic neck reflex to their advantage in performing these crude movements. To test this hypothesis, he sectioned dorsal roots higher than C3 bilaterally. Following this, the limb appeared flaccid and the associative movements previously seen in the limb while the animal was ambulating were abolished. These results were replicated in a later study by Denny-Brown (1966). In attempting to reconcile Lassek's and Twitchell's findings, it should be recalled that Lassek deafferented his monkeys as high as C2, presumably abolishing the tonic neck reflex if there was no C1, whereas Twitchell originally deafferented his monkeys only up to C3.

Researchers have emphasized the necessity of severing all dorsal roots when studying recovery of function in the deafferent. Mott and Sherrington (1895) reported that if the C8 dorsal root was left intact while the other roots (C4-T4) were severed, then the limb showed very little impairment, which they described as "weakness" rather than "clumsiness." The monkey was able to use this partially deafferented limb to pick-up food, climb, and grasp with the hand, although the strength of the grasp was much less than that in the intact hand. Similarly, in comparing animals with a completely deafferented limb with those with a partially deafferented limb, Lassek (1953b) emphasized the degree of movement available to animals in whom one root was left intact. Little impairment was found when the intact root was C6, C7 or C8, whereas, severe impairment was noted when all roots were cut except C5 or T1. Twitchell (1954) also noted that partially deafferented monkeys, in which C6, C7, C8 or T1 was not severed, showed little deficit in function. The animals could climb, ambulate, grasp and perform fine motor coordination, such as opposition of the thumb and index finger. Monkeys in which the C5 or T2 roots were spared displayed deficits resembling the completely deafferented animal. The degree of deficit when only T1 is spared needs to be re-investigated, since Lassek and Twitchell reported opposite results.

Not all researchers who have observed deafferents have arrived at the same conclusions concerning the nature of the deficits. In a review of the early work in this field, Nathan and Sears (1960) discussed the findings of Hering and Munk who independently reported recovery of function after deafferentation in monkeys. Hering (1897), who worked in Sherrington's laboratory in Liverpool, mentioned that he observed one of Sherrington's animals extending its deafferented arm to reach for food--clearly a purposive movement which apparently had been missed by Mott and Sherrington. Munk (1909) observed monkeys making purposive movements by using their deafferented limbs to pick-up food and bring it to their mouth. He stressed that this behavior was particularly noticeable after they had been food deprived, had the intact limb restrained and had food reinforcement given even for unsuccessful attempts. Although Munk found a good deal of recovery of functional movement in the deafferented limbs of his monkeys, they were by no means normal movements; instead, their movements appeared to be "ataxic, dysmetric and clumsy." He agreed with Mott and Sherrington (1895) that the deafferented limb was not used in associative movements with the other limbs as in ambulation. It was these observations that prompted Munk to conclude that the major deficit in deafferented monkeys was with associative movements and not with purposive movements of the limb by itself.

Munk's (1909) report that he was able to induce a monkey to perform a purposive movement with its deafferented forelimb was one of the forces behind a systematic study of the effects of deafferentation which began with a publication in 1958 by Knapp, Taub, and Berman. These investigators were also encouraged to embark on their study by findings of Beck and Doty (1957). The latter researchers thought that the learning of a purposive movement (conditioned flexion response) would be eliminated when proprioceptive feedback from the responding limb was abolished. To test this, cats had their responding limb de-efferented by crushing the ventral roots and all muscles made unresponsive to a shock stimulus by injection of bulbocapnine, after which they were given paired presentations of tone and shock. It was found that testing to the CS alone, after the bulbocapnine had been metabolized and after reinnervation of the responding limb, produced consistent conditioned flexion responses. The authors suggested therefore that some central mechanism was alone responsible for the learning of a conditioned response.

Knapp et al. (1958) trained a conditioned flexion response to a buzzer to avoid shock in normal monkeys who were chaired and not permitted to view their limbs throughout the experiment. After training, all monkeys were unilaterally deafferented (C3-T2), and after postoperative recovery it was found that the deafferented limb could be reconditioned to make the flexion response.

Although Knapp et al. (1958) reported that they did not observe their monkeys making any head and neck movements during reconditioning, a follow-up study was done to rule out the possibility that the tonic neck reflex, previously investigated by Twitchell (1954), may have provided proprioceptive cues for the animal. Therefore, Knapp, Taub, and Berman (1959) unilaterally deafferented (C2-T3) two groups of monkeys one of which had the contralateral dorsal roots from C2 to C4 also sectioned. The same conditioned flexion response procedures were performed and no differences between the two groups were observed. These findings were replicated in a more detailed study by Knapp, Taub, and Berman (1963), who also noted that monkeys could learn a conditioned flexion response with their unilaterally deafferented limbs without having had any preoperative training.

Knapp et al. (1963) helped to clarify the differences between Munk's (1909) and Mott and Sherrington's (1895) findings in unilaterally deafferented monkeys. They noted the following: 1) when the intact limb was immobilized by having the monkey wear a strait jacket, the deafferented limb was used to reach, grasp, pick-up and bring food to the animal's mouth; 2) the same results could be obtained by subjecting the unilaterally deafferented monkey to deafferentation of its contralateral limb, and 3) the monkeys were able to use their forelimbs to perform associative movements, as in ambulating, after both limbs had been deafferented.

Taub and Berman (1963) made an attempt to eliminate any exteroceptive cues that the monkey might rely on to perform a purposeful movement. Specifically, it was felt that since the flexion response (CR) by the monkey's deafferented limb terminated the buzzer (CS), a secondary source of feedback information may have inadvertently been given to the animal in all previous studies in which a conditioned flexion response was used to demonstrate a purposive movement. Therefore, a click CS was substituted for the buzzer precluding the establishment of a response-produced secondary reinforcement using auditory feedback pathways. Unilaterally deafferented (C2-T3) monkeys demonstrated little difference in their ability to learn the conditioned flexion response whether the CS was a click or, as in previous studies, a response terminated buzzer.

Since the previous study used preoperatively trained monkeys, another experiment was performed in which only postoperative training was given to unilaterally deafferented monkeys (Taub, Bacon, & Berman, 1965). Although the same results were found, deafferents took longer to learn the conditioned flexion response in comparison to intact monkeys. Furthermore, Taub, Teodoru, Ellman, Bloom, and Berman, (1966) found that bilaterally deafferented monkeys extinguished a conditioned flexion response more slowly than normal monkeys presumably due to lack of proprioceptive information about the types of movements made by a limb not under visual guidance.

These studies, along with the study by Knapp et al. (1963) in which only postoperative training was used, lent support to the hypothesis that learning a skilled movement can be mediated by central feedback processes without the aid of peripheral feedback. In this regard, Konorski (1961) proposed central feedback loops which may be used to inform the brain about a movement in the absence of proprioceptive feedback.

In an effort to further decrease the amount of peripheral sensory information available to the monkey, the area of deafferentation was extended to include C2 to T3 bilaterally and T4 to S2 unilaterally (Berman, Taub, Pomina, & Knapp, 1960) which resulted in the limb posture remaining the same. Later, a total body deafferentation was achieved (Taub & Berman, 1964), and it was reported that all animals were still able to perform the conditioned flexion response. The authors also noted that bilaterally deafferented (C2-T3) monkeys, after two to four months of postoperative recovery, demonstrated a remarkable amount of motor ability. The monkeys could grasp, pick-up food between thumb and forefinger and move their limbs in the proper sequence during walking and climbing in the free situation. Moreover, they were still able to demonstrate a wide range of coordinated movements including climbing when blindfolded. They were able to make sequential stepping movements when their hindlimbs were raised forcing the animal to support and walk on its forelimbs. These findings throw a considerable amount of doubt on the reflexological explanation used by Sherrington (1906a) to account for sequential and associative movements seen in ambulation. With a totally deafferented monkey all spinal reflex arcs are presumably interrupted, so that a chaining of stretch reflexes can no longer account for the monkey's ability to make purposive movements in a sequential manner.

Since a flexion response of the deafferented limb at the elbow is a relatively gross muscular movement, it remained possible that lack of proprioceptive feedback might prove to be more detrimental for the recovery of function of distal musculature of the hand, where finer and more complex movements can be performed. To test for this, a pressure transducer was placed into a fluid-filled plastic bottle which was taped to the monkey's hand (Taub, Ellman & Berman, 1964; 1966). Bilaterally deafferented naive monkeys were able to grasp the bottle and maintain enough pressure to avoid shock after an initial shaping period, which included the use of vision. It should be pointed out, however, that the buzzer CS remained on until the strength of the monkey's grasp was sufficient to meet the pressure necessary to avoid shock. Secondary reinforcement, giving immediate sensory information, was therefore available. Taub et al. (1966) also reported that when the contralateral deafferented limb was used, the monkeys performed the conditioned grasp response almost immediately, while intact control animals did not perform the response with the untrained hand for the first few trials. It was felt that bilateral deafferentation eliminated the inhibitory effect that the movement of one limb would have on the contralateral limb, thereby facilitating transfer of a conditioned response.

Differences in recovery of function, especially in the free situation, between bilaterally and unilaterally deafferented monkeys were known since the work by Knapp et al. (1963). Taub et al. (1966), and Berman and Taub (1966) implied that the immobility displayed by the unilaterally deafferented limb in the free situation might in part be explained by cross-spinal inhibition from the intact limb. In the normal animal, it is assumed that afferent input from one limb is kept in check by afferent input from the contralateral limb. They suggested, therefore, that afferent input arising from movements of the intact limb might inhibit motoneurons of the deafferented limb thereby restricting movements from it (Taub & Berman, 1968). This hypothesis was systematically investigated in a series of experiments using unilaterally deafferented (C2-T3) monkeys. When the intact limb was amputated at the shoulder, there was no apparent increase in the use of the deafferented limb in the free situation although the monkeys would reach through an opening in a box to obtain food (Berman, 1970; Berman, Teodoru, & Uygur, 1971). Another group of monkeys had the intact limb amputated at the wrist, and they persisted in using the stumb to retrieve food from the box, even though unsuccessful, until the stump was heavily bandaged to preclude its entry into the hole in the food box. At this point, the deafferented limb was successfully used to obtain food as well as for defense and for climbing. Since cross-spinal inhibition could not account for these results the interaction of several other mechanisms was considered, such as attention being less focused on the bandaged stump because of its ineffectiveness, increased motivation, and an increased probability of reinforcement with each successful retrieval of food with the deafferented limb. Berman et al. (1971) also noted that monkeys would spontaneously switch to using the deafferented limb to retrieve food if there were relatively few pieces of food in the box, so that they did not have the visual reinforcement of balancing a piece of food on the stump while trying unsuccessfully to guide it through the hole of the food box.

It was thus shown that movements of the elbow and shoulder of the wrist-amputated limb did not preclude use of the contralateral deafferented limb; however, it was still considered possible that movements of the intact hand and fingers could effect cross-spinal inhibition. To test this hypothesis, unilaterally deafferented monkeys had their contralateral hand encased in a plastic bottle which permitted free movement of the hand and fingers within and would fit through the hole in the food box (Berman, Derasmo, Marti, & Berman, 1975). Testing began 10 days postoperatively, and two monkeys began using the deafferented hand by the fifth test session. In one monkey, the bottled hand was used exclusively for almost a month with no successes; however, when retested after an additional 20 days of rest, this animal used the deafferented limb almost immediately. If the bottle was then removed, all three monkeys soon began to use the intact limb, but would revert very quickly to use of the deafferented limb as soon as the intact limb was made ineffective by bottling.

One conclusion was that purposive movement of a unilaterally deafferented limb did not depend on cross-spinal inhibition but was dependent on the amount of postoperative time, the amount of postoperative experience using the limb, and the degree to which the motivational situation encouraged initial use of the limb. It was also noted that once the animal was forced to use the deafferented limb in the experiment for the retrieval of food, the monkey continued to use that limb in the free situation. Further support for forced use of the deafferented limb came from a study by Taub, Barro, Parker, and Gorska (1972) in which the intact limb of unilaterally deafferented monkeys was restrained in a strait jacket for three days, following which the animal made purposive movements of the deafferented limb in a free situation on a "permanent" basis. As a result of these observations, it was felt that the postoperative animal learned not to use the deafferented limb, and by the time the animal had recovered sufficiently from the surgery to be trained, it had already established a habit of disuse which required strong conditioning techniques (hunger-motivation and/or shock-punishment) to force the animal to break the disuse habit and make use of the deafferented limb. However, Berman et al. (1975) disagreed with the postoperatively learned disuse hypothesis. These authors presented evidence supporting the view that the use of a unilaterally deafferented limb is inversely related to the degree of use of the contralateral limb.

Several authors have investigated the aftereffects of a prismatically displaced visual field on a deafferent's ability to make precise reaching movements. Taub, Goldberg, Bossom, and Berman (1966) conditioned deafferents to make reaching movements toward one of three randomly presented visual targets, with a gradual reduction in the animal's dependence upon visual guidance of the limb until it could make the required movements without seeing the limb. At this point, the monkey wore prisms for 24 hours to distort its visual field, after which, the animal was tested without visual guidance for any aftereffects on reaching behavior. The authors reported that deafferents maintained a 100% aftereffect when they were tested after the prisms were removed, while only a 39% aftereffect was reported for normal animals. It appeared as though deafferents fully adapted to wearing the prisms with a complete recalibration of their visuo-motor coordination since proprioception, which would have normally checked the degree of recalibration, had been eliminated. Bossom and Ommaya (1968) found that deafferents did not differ significantly from normal monkeys in the size of the errors made while adjusting to prisms in a similar reaching task to the one used by Taub et al. (1966). In summary, lack of proprioception seemed to greatly enhance prism aftereffects while not impairing prism adaptation.

Although deafferents can learn new movements postoperatively, it is possible that all patterns of movement necessary for new learning had been laid down during early motor experiences, after birth or even in utero. Gooddy

(1949) felt that the motor cortex initiated purposive movements after receiving muscle and joint information via the afferent system and that this process began very early in the ontogenetic development of the nervous system. One of the first studies to report on the effect of deafferentation on the recovery of motor function in young animals was Lassek and Moyer (1953). Four kittens, 12 to 13 days of age, were unilaterally deafferented from C5-T2 or T3, and one 4 week old monkey was unilaterally deafferented from C3-T4. After 4 months of observation, the four kittens showed no increase in their recovery of motor function beyond that observed during the postoperative period, i.e. the limb was flung forward and high while walking; the limb exhibited "fatigue or inhibition" quite rapidly, causing the animal to drag the limb, and the distal musculature showed the greatest deficit in motor control. The infant monkey was observed for 6 months and showed some increased use of the deafferented limb such as climbing and thrusting the arm through the wire mesh for support. The monkey did not use the hand or fingers, and there was no strength in the grip of the hand, although the animal could reach and grasp when the intact limb was restrained. The authors concluded that afferent input via the dorsal roots was necessary for the normal ontogenetic development of the motor system.

More recent studies have reported on the effect of forelimb deafferentation on the recovery of motor function in infant monkeys. One group of investigators bilaterally deafferented their infant monkeys within hours after birth and reported a remarkable amount of spontaneous functional recovery including ambulation, climbing and reaching for objects (Taub, Perella, & Barro, 1972a, b, 1973). No spontaneous recovery was observed for accuracy of eye-hand coordination, approximation of thumb and forefinger, and individual use of the fingers. However, all of these behaviors improved considerably following the use of specific training techniques to increase hand and finger usage. Two other infant monkeys were bilaterally deafferented and had their eyelids sutured, in order to test the hypothesis that vision may have been sufficient to enable such a remarkable amount of motor function to manifest itself without somatic feedback (Taub, Perella, & Barro, 1972c, 1973). They demonstrated the same degree of purposive movements as the deafferented infants with vision, including a conditioned reaching response away from the body. The deafferented and blinded infants required about one to two weeks additional time before being able to perform each purposive movement in comparison to the deafferented only group. In a similar study, Berman, A. J. and Berman, D. (1973) performed a bilateral deafferentation in three fetal monkeys and a unilateral deafferentation in one fetal monkey all of which were delivered by caesarian section. The bilaterally deafferented animals were able to ambulate, jump and make reaching movements, although inaccurately, within the first month postoperatively. They showed the ability to grasp and hold their own weight, but when vision was precluded, the grip was released. The infants did not climb or use their fingers to pick-up objects, although it was reported that they were very active. The authors felt that proprioceptive feedback was not necessary for the postnatal elaboration of ambulatory movements; however, for purposive movements of the hands and fingers, somatic feedback was necessary since vision alone was not sufficient for the development of these movements. The greater use of the deafferented limbs in the infant monkeys reported by Taub and his group may have been related to five factors: 1) prior motor experience since his animals were deafferented several hours after birth; 2) group use of a "gymnasium" several hours per day, geared toward the development of motor activity; 3) specific conditioning techniques used to promote muscle coordination in reaching tasks; 4) surgical factors in both groups, and 5) group stimulation.

In recent years, an emphasis has been placed on delineating the role of vision in the recovery of function in deafferented limbs with particular attention being placed on the difficulty exhibited by deafferents in performing purposive movements directed away from themselves. In research already reviewed in this report, the following points were made: 1) when vision was occluded and specific training was provided, deafferents were able to demonstrate purposive movements almost as well as deafferents with vision (Taub et al., 1966; Taub, 1968; Taub & Berman, 1968; Taub et al., 1973), and 2) most of the training procedures involved a conditioned flexion response (reviewed by Taub & Berman, 1968) where the forearm was flexed at the elbow toward the animal's body, in which case, the animal could use its own body as a reference point. These observations set the stage for a number of additional studies. First, it remained to be seen whether the vision available to deafferents outside of the experimental situation was the primary source of feedback being utilized by them in the recovery of spontaneous reaching movements with the deafferented limb. In a recent study by Gianutsos and Berman (1975), monkeys who had their eyelids sutured one month before they were bilaterally deafferented did not spontaneously use their limbs for reaching movements made away from their bodies; whereas, deafferents with vision intact could reach and grasp objects located away from themselves. Second, it was necessary to determine the role of vision in a more complex reaching task. Using a task similar to the one reported by Taub et al. (1966) and by Bossom and Ommaya (1968), Taub, E., Goldberg, and Taub, P., (1975) endeavored to ascertain the degree of accuracy that could be trained in a group of deafferents while pointing to one of three targets. Deafferents, with or without visual guidance, were significantly less accurate in their pointing ability than normal monkeys. Moreover, pointing accuracy was shown to decrease in both normal and deafferented animals as the allowed amount of visual guidance of the limb decreased. Gianutsos (unpublished dissertation, 1975) reported that monkeys who had their eyelids sutured before being deafferented could be trained to make a combined reaching and multiple tapping response, but only after a long and tedious shaping procedure. The performance of these animals was worse than deafferented animals with vision, who in turn did not do as well as normal monkeys.

Third, this latter observation pointed to the necessity of determining the importance of sources of peripheral feedback in addition to vision in the deafferent's ability to perform purposeful movements.

A detailed analysis showing the dependence of visually deprived deafferents on exteroceptive feedback has been described by Taub, Schlossberg, Teodoru, and Barro (unpublished manuscript, 1975). Their animals were not able to adjust the strength of a conditioned flexion response to increased resistance placed on the forearm of the deafferented limb when the CS was a click. However, when the CS was a response terminable buzzer, they were able to adjust the force of the flexion contraction almost as well as normal animals. In an earlier study (Taub, et al., 1966), deafferents were able to maintain a required amount of pressure on a fluid filled container in a conditioned grasp response again through the probable use of the response terminable buzzer, but, in that study, the animals also had the opportunity of viewing their response limb during the early stages of training. In summary, it would seem that central feedback processes alone may not be sufficient for a deafferent to learn complex motor tasks in which the animal must make changes in the direction or in the force of the response, especially when exteroceptive sources of peripheral feedback are eliminated or reduced.

Theories Accounting for Purposive Behavior Following Deafferentation

One possible explanation for the successful performance by deafferented monkeys on reaching tasks is that they develop a memory trace or a perceptual-motor map of the target locations. Some evidence in support of a perceptual-motor map comes from experiments on the development of visually guided reaching. Several investigators provided evidence supporting the view that visually guided locomotion or proprioceptive information from active movements are used to mark target positions onto a central map of visual space (in kittens, Held, 1974; in monkeys, Held & Bauer, 1974; in man, Paillard & Brouchon, 1974). Such a map could be used to elaborate a complex motor program of spatially coordinated movements.

Memory trace, perceptual trace, cognitive map and perceptual-motor map are theoretical constructs that have been incorporated into several theories of motor learning, (e.g. Adams, 1971 and Schmidt, 1975). Schmidt (1974) believes that efferent copy of motor commands is not necessary for learning new movements, only a record that a motor program has run itself off. He suggests that a motor response schema or program can be slowly established over many trials on the basis of stored information about pre-movement factors, such as experimental expectations and motor requirements, as well as post-movement factors, such as response-produced sensory information and knowledge of results of a motor movement. This schema incorporates a recall memory responsible for a movement and a recognition memory which serves as a comparator to detect errors in efferent commands and make corrections. Schmidt's theory would predict that monkeys with no proprioceptive feedback would have difficulty in learning a spatial task but that they have the requisites for a schema to develop and would, in fact, be able to learn the task. In studies on deafferentation where conditioning techniques are used, knowledge of experimental conditions and motor requirements are provided via the shaping procedure. Response-produced sensory information and knowledge of the results of the movement are provided immediately via noise from the pellet or fluid dispenser followed by the delivery of the reinforcement and its consumption after each correct response or sequence of correct responses. According to Schmidt, the schema is then constructed from afferent information and is used to generate efferent commands which are themselves recorded, to be recalled on the next trial and altered if necessary.

To make an appropriate limb movement in a motor learning paradigm, according to Adam's theory, three essentials are necessary: a record of past movements ("perceptual trace"), a knowledge of the results of the last movement, and feedback information on the position of the moving limb. Adams (1971) stresses the informational and motivational aspects of knowledge of results on each trial in order to detect an error and make a more correct response on the next trial. Not only proprioceptive but auditory and visual feedback can serve to enhance a trace on each trial. When response-produced feedback stimuli match a perceptual trace then the strength of the trace increases enabling the subject to recognize a previously made response.

Adams (1971) postulated another construct which he calls the "memory trace" that acted without feedback and therefore before the perceptual trace. It functioned to organize and start a particular response. Both Adams and Schmidt claim that verbal learning data supports the idea that recall and recognition functions are two separate processes within the same motor movement. Motor recall is used to initiate the movement based upon the memory trace, while response recognition is necessary to decide the correctness of the movement based upon the perceptual trace and present feedback information from the movement in progress. "The memory trace applies only to the selection and initiation of the movement, while the perceptual trace governs movement extent" (p. 126). Thus, the memory trace is like a miniature motor program that needs to be cued into firing.

Knowledge of results cannot be overemphasized as a part of any explanation of the performance by deafferents. Evarts (1971) stated that "when response feedback is eliminated by deafferentation, it is still possible that feedback generated internally or by knowledge of results may be of critical importance in motor control" (p. 104). Several investigators of the learning of skilled movements by deafferents with vision occluded, have stressed the importance of knowledge of results, particularly in the form of auditory information, informing the animal of the consequences of its response (Gianutsos, unpublished dissertation, 1975; Gianutsos & Berman, 1975; Taub et al., unpublished manuscript 1975). Non-topographic sources of feedback that provide the monkey with consequential response information and information on the sequence of muscle movements have also been mentioned by Bossom (1974), Taub et al. (1965, 1975) and Taub and Berman (1968).

Deafferented monkeys might be able to utilize proprioceptive information from movements of eyes. Two questions are relevant. First, do proprioceptive receptors exist in extraocular eye muscles, and second, does an animal utilize such information, if it exists. It has been demonstrated that muscle spindles do exist, on histological and physiological examinations, in all extraocular muscles in many mammals including man and the chimpanzee (Cooper & Daniel, 1949). The presence of muscle spindles in the eye muscles of the macaque monkey, cat or dog, however, was not confirmed by Cooper and Daniel (1949). The authors felt that this was because head and neck movements were used more extensively than eye movements in these animals.

As for the second question, Cooper, Daniel and Whitteridge (1951) and Crawford (1960) demonstrated proprioceptive feedback control of eye movements. Cooper et al., (1951) showed that eye muscles in goats and sheep were extremely sensitive to stretch. Afferent discharges were recorded in the oculomotor nerve which increased rapidly when the muscle was passively stretched. Calculations revealed that proprioceptors in extraocular muscles could detect eye movements under 1.5 degrees. They concluded that the oculomotor system is sensitive enough to play some role in eye movement control. In another study, Crawford (1960) described an experiment in which errors of less than two degrees were observed in human subjects when aligning the head with a lit target in darkness. The author concluded that the subjects were dependent upon position of the eyes with respect to head movement, although he admitted that position sense may have originated from an extra orbital structure.

Contrary to the above findings, Ludvigh (1952) found, in humans, that the eye had to move a minimum of 6 to 10 degrees before the subject reliably reported that the eye had moved in a particular direction. (A 0.2 degree passive movement of the hip joint is discriminable.) He also noted that the subject's reliability was greater when detecting vertical than horizontal eye movements. This finding suggested that the levator palpebrae muscle was furnishing more proprioceptive information with vertical eye movements and may have also contributed to the detection of horizontal movements. These results made it even less likely that proprioceptive in extraocular muscles were responsible for detecting eye movements.

Other studies in man also support the findings of Ludvigh (1952). Merton (1961) showed that fixating an object in the dark, after locating it in the light, resulted in a 1 degree S. D. This was considered to be a significant increase in the magnitude of error since successive fixations in the light resulted in a S. D. of 5 minutes of arc. He concluded that if position sense were available from eye muscles it certainly was not being utilized. Furthermore, Merton (1964a) found no evidence for position sense in human eyes during passive or active movement of the eyeball. When the surface of the eye and surrounding tissues were anesthetized and the cornea was covered, the subject was unable to detect eyeball movements of 20 degrees or more by passive pulling on an extraocular muscle. The same results were obtained when both eyes were passively moved simultaneously. Subjects were not able to detect whether their eye had been restrained or was free to move when they were asked to move voluntarily the eye while the experimenter held the extraocular muscle precluding actual eye movement. These studies showed that humans were not consciously aware of position sense and that "a subject is only conscious of his intention to move his eye and does not know whether the movement has in fact taken place or not" (p. 318).

In summary, several authors have reviewed the evidence for the presence of proprioceptive information from extraocular muscles, and, as Festinger and Canon (1965) concluded, they are not in agreement as to whether afferent signals from extraocular muscles could be utilized in the control of eye movements. Matin, L., Matin, E., and Pearce (1969) stated that there was no evidence to show that muscle spindles in extraocular muscles give proprioceptive feedback information useful to the subject in reporting directional changes in his visual field. Merton (1961, 1964a, 1964b) made a strong case supporting Helmholtz's 'sense of effort' hypothesis that "the human eyes are without conscious position sense and that, in the absence of visual clues, we only know how far we have moved our eyes by judging the effort of will put into moving them" (Merton, 1961, p. 555). Holst and Mittelstaedt (1950/1973) commented that the functional significance of extraocular muscle receptors has been overstated probably because there are no provisions for central feedback processes in reflexology.

Another source of proprioceptive feedback, the vestibular system, is of particular relevance because head movements have not been restricted in deafferentation research. Since the head turns in the direction of a saccadic eye movement within 20 to 40 millisec after the saccade (Bizzi, 1974), head movements may be utilized by deafferents in controlling limb movements (Taub & Berman, 1968). The literature cited by Bossom and Ommaya (1968) supports the importance of active head movements in deafferents for the correction of limb movements during exposure to prisms. In addition, vestibular reflexes are among the first to recover in a deafferented animal (Denny-Brown, 1966; Goldberger & Murray, 1974).

It is possible that monkeys learned to stimulate innervated areas of the body with the deafferented limb to obtain sensory information as to the position of the limb. A related possibility is that movements of the deafferented limb might have stretched skin and muscles of intact areas providing the animal with relevant somatic sensation. Both types of feedback might be correlated with efferent commands facilitating the learning of correct movements. Kirk and

Denny-Brown (1970) found that the area of sensitivity from intact dermatomes surrounding a deafferented area progressively increased over the first week following deafferentation. In addition, at the border of these enlarged dermatomes, there were areas of hyperesthesia. They noted that the size of the dermatome was "dependent on facilitation mediated by intact neighboring sensory roots" (p. 319). It has also been reported that the receptive fields of intact dorsal roots, within the gracile nucleus, increased in size after partial deafferentation in cats (Millar, Basbaum, & Wall, 1976).

Central processes has been suggested by most authors involved in deafferentation research, as one of the mechanisms responsible for at least some of the performance by deafferented monkeys (Taub & Berman, 1968). Various authors have referred to such processes as central feedback, corollary discharge, re-afference and efferent monitoring (Evarts, 1971). Although they are often discussed independently, any one or all of them may provide enough central feedback to allow the deafferent to make purposive limb movements without exteroceptive feedback. For the purpose of this discussion, corollary discharge is considered the primary central process by which efferent information is reported back to the central nervous system. Re-afference and efferent monitoring are considered as theoretical mechanisms to explain purposive movements.

A review of the literature on deafferentation in the cat, dog and monkey shows considerable support for the view that stepping movements are centrally controlled (DeLong, 1971). Such a position was advocated as early as 1911 by Brown who postulated central control of stepping in the cat with proprioception playing a "regulative" and not a "causative" role. Proprioception would function to inform the organism of the position of his limb allowing the central nervous system to modify its program for stepping movements accordingly. In the cat, Engberg and Lundberg (1969) demonstrated electromyographically that extensor muscle activity was initiated before the paw had touched the ground. Since muscle spindles could not have been activated to give proprioceptive feedback before muscle activity, the authors concluded that stepping was a centrally programmed activity. Proprioception was thought to be responsible for modifying muscle movements during stepping but not to initiate the movements. Vaughan, Gross, and Bossom (1970) proposed that proprioception did not normally stimulate motor cortex during muscle movements. Preceding a movement there was a negative waveform component of the motor potential followed by a positive component which began after the movement and was thought to be due to kinesthetic feedback. This suggests that proprioception was not used to initiate movements but rather to signal the position of the limb, so that an appropriate error signal could be emitted to correct movements. In addition, Brooks, Jasper, Patton, Purpura, and Brookhart (1970) noted that, when muscle movements were timed during the act of stepping, proprioceptive information from stretch receptors could not possibly be utilized since the sequence of movements were too rapid. These authors also reported a number of changes in neural activity prior to the onset of movement, which included firing of corticospinal neurons, cessation in the spontaneous activity of purkinje cells, sudden increase in activity from intrinsic cerebellar nuclei, and repetitive firing of cells in VL -- all of which may be involved with central feedback.

Sperry (1950) was one of the early investigators to propose "that a corollary discharge of motor patterns into the sensorioum may play an important adjustor role in the visual perception of movement" (p. 489). He used the term corollary discharge to explain the spontaneous optokinetic response or circling behavior in fish after eye rotation and extirpation of forebrain, cerebellum and labyrinth. Teuber (1960, 1964) referred to corollary discharge as a massive neural firing from the motor to the sensory system before sensory feedback occurs. A voluntary and not a passive movement produces a corollary discharge which primes the central nervous system to expect a re-afferent signal (Teuber, 1964).

There is electrophysiological and anatomical support for the existence of central feedback loops which may be the corollary pathways. Much of the early literature on pyramidal tract collaterals to dorsal column nuclei has been reviewed by Levitt, Carreras, Liu, and Chambers (1964). They concluded that stimulation of the sensorimotor cortex excited dorsal column nuclei via the pyramidal tract and inhibited these nuclei via the extrapyramidal system. Axonal degeneration from lesions in primary sensorimotor cortex was traced to gracile and cuneate nuclei. Anatomical support for the existence of collaterals from pyramidal tract neurons in monkeys was provided by Kuypers (1960).

Teuber (1964) reviewed electrophysiological studies that showed brain stem structures monitoring pyramidal tract activity from motor cortex and relaying the information back to cortex. There is electrophysiological support for the existence of connections from pyramidal neurons to VL of the thalamus (Clare, Landau, & Bishop, 1964), to VL and ascending reticular system (Li, 1958), and to dorsal column nuclei (Guzman-Flores, Buendia, & Lindsley, 1961; Guzman-Flores, Gault, Anderson, & Lindsley, 1963). It has been shown in the monkey that, prior to the execution of a learned movement and before any response feedback could reach the central nervous system, discharges occurred from VL nucleus (Evarts, 1970), pyramidal tract neurons (Lewis & Porter, 1974), cerebellar neurons in dentate and interposed nuclei (Thach, 1970a) and Purkinje cells (Thach, 1970b). Guzman-Flores et al., (1963) demonstrated in the cat a facilitatory effect on the transmission of afferent signals through dorsal column nuclei after stimulation of VPL of the thalamus. Similar results were found by Adkins, Morse, and Towe (1966) after stimulation of the pyramidal tract. They theorized that cortical output could directly enhance its own output. This was further supported by a study in which stimulation of the medullary pyramid in rabbits caused an electrical response in motor cortex of sufficient latency that it must have been produced by collaterals from pyramidal neurons (Chang, 1955).

In summary, there is ample evidence for central feedback loops serving as corollary pathways.

One theoretical mechanism that has been used to explain purposive movements is re-afference. Holst (1954) stressed the role of the central nervous system as a mediator among proprioceptive signals from muscles which he called "re-afference," afferent signals from external sources which he called "ex-afference" and motor signals to muscles which he called "efference." A re-afference principle has been described by Holst and Mittelstaedt (1950/1973). When a neural center sends an efferent command to a muscle, an efference copy or corollary discharge of that command is sent to other neural centers. If changes in ex-afference result in greater or lesser re-afference when compared to the efference copy, then the remainder acts on a neural center to alter the efferent command and effect a correction. The process is continued until a balance is achieved between efference copy and re-afference, similar to a servomechanism. A similar theory was suggested in 1950 by Sperry and developed more recently by Teuber (1960, 1964) and MacKay (1966).

An elaboration on the Holst model by Hein and Held (1962) includes the suggestion of a memory component which correlates and stores efferent and reafferent traces. The authors state that "the currently monitored efferent signal is presumed to select the trace combination containing the identical efferent part and to activate the re-afferent trace combined with it" (p. 73). A comparison is made between the linked re-afferent signal and the incoming re-afferent signal in a neural center which acts to make corrections based on their compatability. Hein and Held refer to this neural center as a "comparator." The ability of a particular efferent command to evoke the same efferent/re-afferent signal depends upon the success of the outcome. The more equally-weighted alternatives there are in the comparator the more variable the response.

Experimental support for this model comes from a number of experiments on visually elicited or guided movements. It has been demonstrated in kittens that the presence of both patterned light and viewing of the limbs during locomotion were required before visually guided movements could be made (Hein, 1970). When kittens were passively transported in patterned light, however, they failed to show a limb extension response even though they could move about within the transport box and view the moving environment (Hein, Held, & Gower, 1970). These data suggest that the retinal image had to be correlated with self-produced movements before visually elicited extension or visually guided behavior could be developed (Hein, 1970). Passive transport prevented visual stimulation from the moving environment from being correlated with the animal's limb movements within the transport box. The result was a mismatch in visuo-motor signals in the central nervous system. In this respect, Bossom and Ommaya (1968) have stressed that there must be matching of visual signals with efferent signals in a comparator in order to account for the gradual correction of misreaching behavior in prism-wearing deafferented monkeys. For a review of the literature on the cerebellum as a neural center which functions as a comparator between peripheral and central inputs for the purpose of detecting and correcting movement errors see Brooks et al., (1970, Evarts (1971), Evarts and Thach (1971).

Another theoretical mechanism that has been used to explain motor performance by deafferents is efferent monitoring. Jones (1974a) suggested that the visual perception of a target in space might provide sufficient information to initiate a rapid limb movement in the direction of a target, and the limb movement would be tracked via central monitoring of efferent signals. However, he noted (1974b) that during the initial learning period some exteroceptive feedback information may be necessary, so that movement errors can be detected by matching efferent commands with exteroceptive feedback. Burke (1971) also emphasized the importance of some afferent information along with central feedback before the latter could evoke a learned movement without exteroceptive feedback.

Jones (1973, 1974a,b) presented evidence suggesting that central monitoring of efferent signals and not proprioceptive feedback is the important factor in the performance of voluntary movements. Blindfolded subjects were not accurate in duplicating a voluntary movement to a pre-arranged stop provided by the experimenter or in duplicating a passive movement. However, accuracy significantly increased when they were allowed to make the same movement on their own volition (Jones, 1972b). Furthermore, the accuracy of ocular tracking a target, mounted on the subject's finger, has been shown to be greater when the subject is required to make voluntary arm movements than when his arm is passively moved (Steinbach & Held, 1968). There is also evidence to support the claim that efferent information going to the hand is received by the oculomotor system, so that this information can be compared with that received from eye movements, all of which is done before any visual stimuli or proprioceptive information from the hand is received in the brain (Angel & Garland, 1972).

Laszlo (1966, 1967) also provided evidence to support the theory that central processes are of significance in monitoring skilled movements. She used a nerve compression block technique to eliminate sensation from the hand while still permitting finger movements (Laszlo, 1966; Laszlo & Bairstow, 1971). With practice, subjects were able to tap a Morse key near the rate of tapping achieved before limb sensation was blocked (Laszlo, 1967). She also noted that when auditory and visual cues were eliminated in addition to proprioception, the tapping rate fell to below half the normal rate suggesting the importance of exteroceptive feedback when proprioception is eliminated. In a subsequent study, Laszlo and Baker (1972) demonstrated near normal performance in writing letters among subjects deprived of limb proprioception but allowed to visually guide the limb in comparison to the severe decrement in performance on the same task when both proprioception and vision were eliminated. It is interesting to note that some motor cortex cells received visual and auditory input via cortical-cortical interconnections as well as connections between midbrain reticular formation and posteriomedial and ventro-lateral thalamic nuclei (Brooks, 1969). All of the above findings further support the necessity for auditory and/or visual cues in the deafferent's recovery of reaching behavior, as has been stressed by Bossom (1974), Gianutsos (unpublished dissertation, 1975), Gianutsos and Berman (1975) and Taub et al. (1975; unpublished manuscript, 1975).

In a previous section, it was noted that proprioceptive receptors do exist in extraocular eye muscles of monkeys but that they do not give useful information as to the position of the eye and therefore do not contribute to the performance of deafferents. It is possible, however, that deafferents might rely on central monitoring of efferent information to eye muscles, and there are data supporting such a view. Matin, L., Matin, E., and Pearce (1969) suggested that the stability of the visual field during eye movements was the result of a synchronization of central efferent commands with retinal afferent signals at some neural structure before perception occurred. In another study, Skavenski, Haddad, and Steinman (1972) independently varied efferent information to eye muscles and afferent information into the oculomotor system from these muscles. They found that the perception of the direction of a target in space was dependent upon efferent information and was not significantly influenced by changes in afferent information.

Further support for the view of central control of eye movements is found in experiments that showed that saccadic and smooth tracking eye movements were independently controlled mechanisms (Rashbass, 1961). Saccadic movements seemed to be dependent upon the location of a target while smooth eye movements were dependent upon the direction and velocity of a target movement. Rashbass suggested two mechanisms: 1) if a saccadic movement were used to bring the eye into position with a target then the efferent impulses generated from the movement of the eye to that position would be responsible for that saccadic eye movement, and 2) if a smooth tracking movement were used to keep the eye on target, then the efferent impulses generated by the tracking movement would supply information as to the direction and velocity of the target movement but not on its location. These two mechanisms were evaluated by Festinger and Canon (1965). They found that target localization was significantly improved when the target was briefly presented at a specific location than when it was tracked to the same location. Target stimulation of the peripheral retina was thought to be the effective stimulus that generated the saccadic eye movement. Efferent impulses from this movement, it was argued, were then used to control arm and hand movement to locate that target accurately. In this respect, it was also suggested that efferent commands from neurons in the superior colliculus could be used to fixate a target by saccades as well as for informing other brain regions via corollary discharge that an eye movement was about to occur (Werner, 1974).

There are a number of neurophysiological changes which alone, or in conjunction with each other, might be responsible for some or all of the recovery of function in deafferented monkeys. One of the effects of removal of afferent input is a compensatory sprouting of other neurons within the deafferented area, called collateral sprouting. In a review of the early literature on the peripheral nervous system, Edds (1953) described collateral sprouting of intact motor and sensory neurons in the rat and monkey after partial denervation of muscle or skin. Within the central nervous system, Ramon y Cajal (1928) reported the formation of new processes from intact neurons within an area of the brain or spinal cord that had been damaged by trauma. For a discussion of possible factors responsible for sprouting see Goodman and Horel (1966). The evidence for and the significance of collateral sprouting is discussed in Appendix I.

There is some evidence that reduced sensory input might indirectly stimulate the development of collateral sprouting. The neurophysiological effect of reduced afferent information on the activity of neurons in motor cortex in relation to motor movement has been investigated in the monkey by Lewis, Porter, and Horne (1971). Afferent input was decreased by injecting a local anesthetic into the wrist of the limb used in a lever pulling task. It was found that as the afferent input was reduced the discharge rate from individual neurons in the precentral gyrus associated with the hand movement significantly increased, thereby compensating for reduced feedback. The authors suggested that reduced afferent input resulted in decreased inhibition on motoneurons allowing them to increase their firing rate and maintain the learned motor response. Since deafferentation eliminates afferent input from the forelimbs, it is quite possible that one among the many compensatory changes might be increased firing from precentral neurons associated with forelimb movements. Such changes might be considered a prerequisite or at least a facilitator in the development of collateral sprouting and/or reliance upon corollary discharge in establishing central feedback mechanisms.

Another effect of removal of neural input is the development of hypersensitivity in the structures denervated. This phenomenon was observed by Cannon in 1939 in denervated smooth muscle, glands, skeletal muscle, and peripheral or spinal nerves. These structures exhibited increased excitability, compared to normally innervated tissues, to electrical stimulation and various chemical agents, such as acetylcholine, strychnine sulphate and concentrated salt solutions. He formulated a "law of denervation" which said, "when in a series of efferent neurones a unit is destroyed, an increased irritability to chemical agents develops in the isolated structure or structures, the effect being maximal in the part directly denervated" (p. 738). Specific examples of denervation hypersensitivity and its significance are discussed in Appendix II.

It has been suggested that denervation hypersensitivity is a non-specific mechanism and that behavioral evidence favors a more selective mechanism, such as collateral sprouting, to explain recovery of motor function in deafferents. This conclusion was based on evidence that descending spinal reflexes recover in deafferented cats (Goldberger & Murray, 1974) while segmental spinal reflexes recover in cats with hemisection of the spinal cord (Murray & Goldberger, 1974); in neither case is there a generalized increase in all reflexes. Furthermore, Chambers, Liu and McCouch (1973) suggested that collateral sprouting could account for most of the demonstrated denervation hypersensitivity. Their suggestion was based on evidence that internuncial potentials increased to the degree that the number of dorsal root afferents increased following spinal cord hemisection.

Some of the proposed mechanisms mentioned to explain denervation hypersensitivity were disuse, changes in levels of chemical mediators and enzymes at the synapse, metabolic changes resulting from degeneration and alterations in membrane permeability (Cannon & Rosenblueth, 1949; Sharpless, 1964). A discussion of these mechanisms concluded that they were essentially unsubstantiated (Sharpless, 1964).

Regeneration is another possibility that has been considered after deafferentation. McCouch (1955) reviewed some of the early work on regenerating nerve fibers in severed dorsal roots and made several observations: 1) regenerating proximal axons react the same way as regenerating distal axons when severed from the ganglion cell, 2) proximal growth of most regenerating axons halts at the junction of the rootlet with the cord, 3) some fibers turn and re-enter the root, others follow blood vessels and enter the cord, and 4) once an axon enters the cord, it continues to grow.

The foregoing suggests that regeneration within the spinal cord might be impeded. Several researchers have explored the possibility of neural regeneration after transection of the spinal cord. Freeman (1955) observed on histological examination of previously transected spinal cord segments in the rat, cat and dog that many nerve fibers regenerated across the transection. Potential recordings were obtained in both directions across the transection in rats which had regained the ability to walk, climb and perch on their hindlimbs. Furthermore, conduction ceased and the initial paraplegia was reinstated when the cord was retransected at the original site. The author stressed the point that the transection be a clean cut, the stumps be immediately approximated, and a tremendous amount of postoperative nursing care be given to achieve success. He also noted that glial and connective tissue scar formations were the greatest obstacles to regeneration, although some nerve fibers were seen to regenerate through the scar. This latter finding was supported by McCouch (1955), who described experiments in which central nervous system regeneration was increased when the animal was treated with piromen, a drug that reduces scar tissue formation. However, Sharpless (1964) concluded that regeneration rarely achieves functional connections, most probably because of scarring. And, in a summary of reports on transection in man, one investigator concluded that regeneration was not possible (Windle, 1955). The few cases where functional regeneration was said to have occurred were thought to be due to a subtotal transection.

If there is one common factor among these neurophysiological mechanisms of hypersensitivity, collateral sprouting, and regeneration, it may be the nervous system's attempt to adjust to changes in excitation of neural structures in order to maintain some constant level of activity which approaches the norm (Sharpless, 1964; Riesen, 1966). It has been suggested by Sharpless (1964) that denervation hypersensitivity represents an increase in neural activity in areas that have had their level of activity reduced, and that collateral sprouting represents a compensatory process of new neuronal growth from intact axons in previously degenerated areas. Likewise, regeneration, where possible, would represent a reconnection of previously injured proximal and distal nerve fibers. The purpose of these mechanisms would be to reestablish a normal level of excitation from injured nervous tissue. It has also been suggested that each mechanism acts as the stimulus for the next mechanism, so that hypersensitivity is a necessary precursor to collateral sprouting which in turn precedes regeneration (Sharpless, 1964). Goldberger and Murray (1974) claimed that "denervation supersensitivity would precede or even stimulate sprouting and then be replaced by the establishment of synapses by collateral sprouts" (p. 35). Behavioral and neurological examination of deafferents supports these time relationships. For example, the rapid appearance of neuronal hypersensitivity following spinal shock from surgery has already been mentioned (see Appendix II). Along with the development of hypersensitivity there was the simultaneous recovery of reflex activity and motor function within the second week postoperatively in cats (Goldberger & Murray, 1974) and in monkeys (Bossom, 1972). The time needed to develop central processes in deafferents might similarly be related to the time needed to form collateral sprouts.

Ventral root afferents may provide an alternative path for proprioceptive information to reach the central nervous system from dorsal rhizotomized limbs. The classical view of the ventral root as the mediator of motor activity dates back to the first half of the eighteenth century and became known as the Bell-Magendie law (Deutsch, J. A. & Deutsch, D., 1966). There exists, however, a substantial body of literature describing structures in the ventral root other than axonal fibers of motor cells located in the ventral and lateral horns of the spinal cord. This literature is discussed in Appendix III and consists of reports on anatomical evidence of afferent fibers and nerve cells in the ventral root, electrophysiological evidence of centripetal conduction along ventral roots, and clinical evidence of failure to relieve pain after dorsal rhizotomy in man.

Another possibility for recovery of function in deafferents is that the deafferentation was not complete. Several investigators have checked for completeness of deafferentation by stimulating cut nerve ends and skin areas on the deafferented limb in order to determine if a cortically evoked response could be recorded via surface electrodes. Berman and Taub (1966), Taub and Berman (1964) and Taub et al. (1965) reported no evidence of an evoked cortical response when the central ends of severed peripheral nerves in the deafferent were electrically stimulated at suprathreshold values. In another study, Bossom and Ammaya (1968) obtained similar negative results even with stimulation of hair follicles and skin. However, Bossom (1974) acknowledged that the techniques used were not sensitive enough to convince him of the completeness of the deafferentation. He recommended that the entire issue be re-investigated, although he did not suggest what methods ought to be used.

In a more recent study, Cohn, Jakniunas, and Taub (1972) attempted to show that electrophysiological verification of deafferentation using scalp electrodes could be considered a "critical determinant of the functional effectiveness of the experimental surgery" (p. 1114). Allison and Goff (1973) criticized this technique, however, on the grounds that scalp recordings are not sensitive enough to prove the absence of an evoked response. In addition, they questioned the adequacy of the actual recordings obtained.

Rationale for the Present Experiment

Recent studies indicated that monkeys deprived of vision before deafferentation never made reaching responses away from their body, unless some source of exteroceptive information, i.e. auditory, was made available (Gianutsos, unpublished dissertation, 1975). However, if the deafferent "was first allowed to see its responding limb throughout its trajectory" during early shaping to reach one of three targets, the monkey could reach the same targets presented in irregular order and without visual guidance (Taub, et al., 1975, p. 180). Visual guidance, given during shaping, may have permitted the laying down of "memory traces" which the deafferent may have utilized during testing when visual guidance was not available. One question then was whether deafferents could perform reaching movements to targets presented in random order when visual guidance of the moving limb was not available during shaping and testing.

An effort was made to devise a method for deafferents to execute movements to briefly lit, spatially separated targets without visual guidance. Once this was achieved, several questions were asked concerning the reaching performance of deafferents. What was the deafferent learning--a target location or a conditioned motor movement? Could the deafferent learn to reach targets presented in random order? Was additional training required to execute new 2-target tasks after the deafferent demonstrated proficiency on previously learned 2-target tasks? Were there savings in learning subsequent 2-and 3-target tasks?

The answers to these questions are of particular relevance because of their theoretical implications. It has been hypothesized (Berman, A. J. & Berman, D., 1973) that continued practice of active movements would lay down a memory trace of a conditioned motor response. If the behavior by deafferents was solely dependent upon conditioned motor movements, then it could be predicted that the deafferent would eventually learn to respond to a fixed sequence of targets but would not learn sequences of targets presented in random order. However, if, after being shaped to reach a second target, deafferents could reach it from a new start target, then the target location interpretation would be supported. The memory trace might be of a target location and not only of the motor response. Further support for this interpretation would be forthcoming if deafferents could perform 2-target tasks presented in random order. Specifically, once deafferents had learned several 2-target tasks separately where only the second targets varied, could they execute the same 2-target tasks presented in random order? Also, could they perform 2-target tasks involving novel second targets as well as 3-target tasks presented in random order? The performance of three bilaterally deafferented monkeys was compared to that of two sham operated monkeys (sham operates).

CHAPTER II

METHOD

Subjects

Five male adolescent rhesus monkeys (Macaca mulatta), weighing six to eight pounds each at the time of surgery, were used as subjects. Three animals (E, F, & G) were deafferented, while the remaining two (H & I) were sham operted.

Surgery

Bilateral deafferentation was performed under aseptic conditions by intradural section of dorsal roots C2-T3 inclusive in order to eliminate all somatic sensation from the neck, shoulders and forelimbs.

The animals were intubated under ketamine hydrochloride anesthesia, so that respiration could be controlled with a ventimeter-ventilator apparatus (Air Shields). The animal was then transferred to an inhalation anesthesia mixture of 50% nitrous oxide and 50% oxygen. Surgical anesthetic level was maintained throughout the procedure with 1/4 to 1/2% halothane. The monkey was placed in the prone position and fitted into a surgical head holder which flexed the cervical spine making it more accessible surgically. A midline longitudinal skin incision was made, and the muscles were retracted to expose the lamina arches. Unipolar coagulation (Bovie) was used to control bleeding.

Operating surgical loupes (Designs for Vision) with three power magnification were now used. Laminectomy was performed from C1 to T4. The dura was incised and retracted with sutures, exposing the spinal cord and dorsal roots. In a systematic manner, each dorsal root or rootlet was separated from companion capillaries and arachnoid attachments, lifted with a neural hook and then coagulated using a bipolar Malis neurocoagulating forceps (Codman & Shurtleff) to minimize extravasation of blood from fine capillaries when the root was transected. The root or rootlet was severed in two places using a fine microsurgical scissor or scalpel, so that a section of the root or rootlet was excised. The entire surgical field was re-examined under 16 and 25 power magnification for any intact dorsal rootlets. For this purpose, fiber optic illumination (designed by Designs for Vision for A. J. Berman) was used. Sham operates underwent the same surgical procedures except that the dorsal roots were not severed. All monkeys were allowed a two week recovery period before training began. This period allowed sufficient time for the animal to recover from surgery and to insure that it had not developed any side effects which might influence the animal's fitness for training. In fact, all animals met the following criteria:

1) no evidence of flaccid paralysis in either hindlimb
2) use of hindlimbs at least to the extent that the animal

could right itself and maintain itself in a sitting position

3) no evidence of mutilation of hands.

Postoperative Care

For the first four days postoperatively, all animals received dexamethasone sodium phosphate (Organon) to reduce spinal cord swelling. Sodium ampicillin was given as a general antibiotic. Once the animals became active and began to move their forelimbs, they were fitted with a helmet (first used and described by Gianutsos, 1975) made from a common kitchen strainer through which the monkeys could see but could not use their teeth to mutilate their limbs. Several layers of surgical drape were stretched over the back of the strainer and sewn around its rim. A slit was made in the center of the drape enabling the experimenter to place the mask over the head of the animal. Two ties were used to close the slit snugly around the animal's neck, thereby preventing the monkey from prying the helmet off. Water was always accessible through the helmet from a metal drinking spout that projected into the cage at a convenient height, without the need for the animal to climb. Food crackers were placed inside the helmet after each experimental session, obviating the need to remove the helmet for feeding. It should be noted that the limbs were not used for feeding, and the animal wore the helmet at all times in the home cage.

Apparatus

During training, each monkey was restrained in a chair facing a response panel consisting of a 3 x 3 display of targets (Fig. 1, 2, and 3). Each target, 1-1/4" square, was made of white translucent plexiglas which could be illuminated from behind. The nine targets were placed into equally spaced square cutouts forming a 7 x 7 in. square in a 10-1/2 x 13-1/2" black plexiglas panel. Metal window screening covered the entire panel, with individual targets electrically insulated and connected to solid state, high input impedance, touch activiated circuits. The entire response panel with nine transilluminated lights and nine solid state circuits was housed in a box which was mounted on the chair in a slotted track and positioned approximately 8 in. from the front of the animal's eyes. This position enabled the monkey to see and touch any one of the targets on the display.

A common lead from the circuits in the response box was connected to the metal seat of the restraining chair. The apparatus was programmed so that touching a lit target completed a circuit and operated a relay. Through a system of nine such relays, a response to a lit target was channeled to a stepping switch which could activate the touch circuit and lamp behind another target, while a response to any of the other eight targets was channeled to an error counter, one for each target. A pellet dispenser was mounted on the left side of the chair, and 190 mg banana flavored pellets were used for reinforcement.

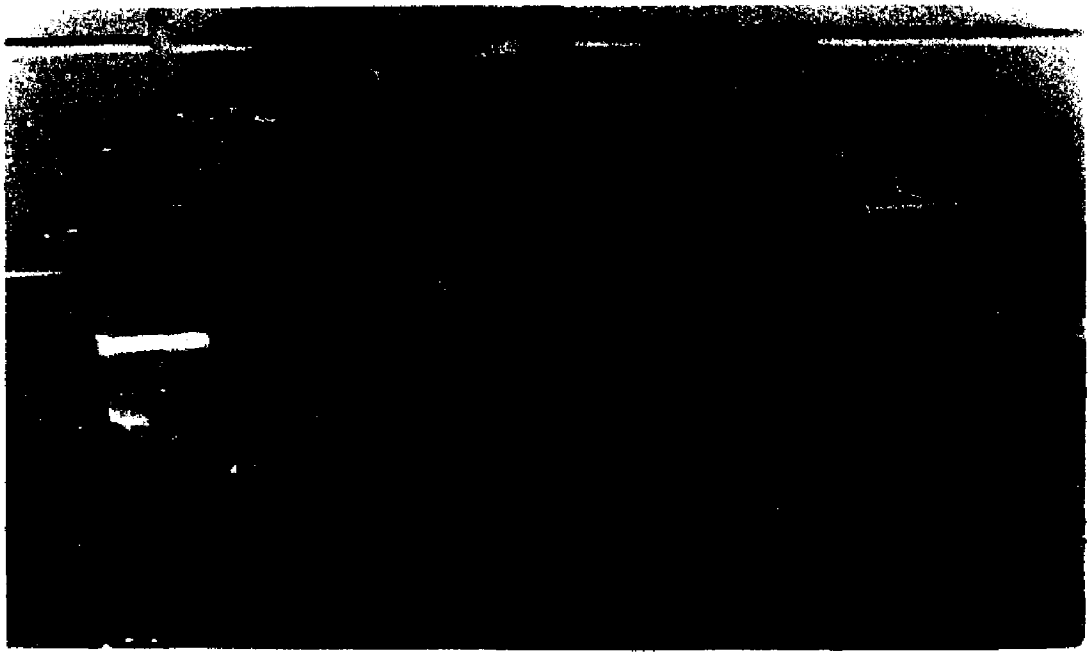

Fig. 1. Profile view of monkey touching target.

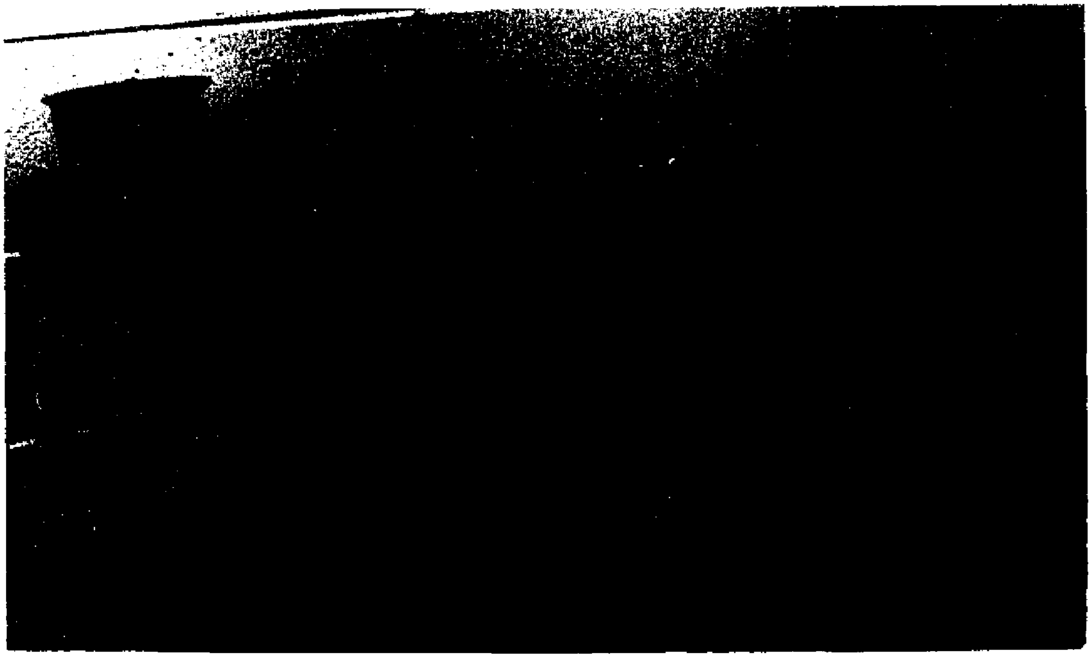

Fig. 2. Rear view of monkey touching target.

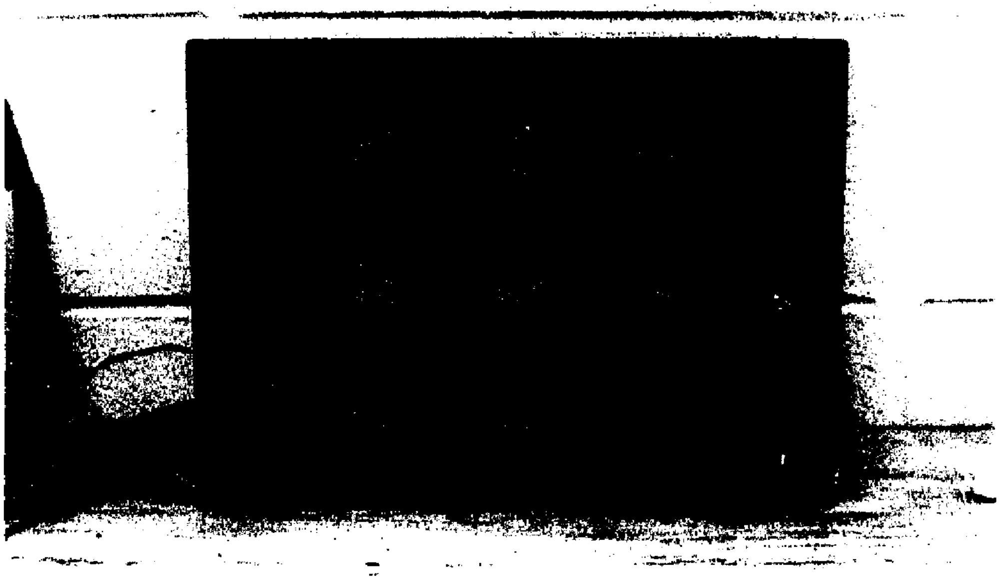

Fig. 3. Front view of response box.

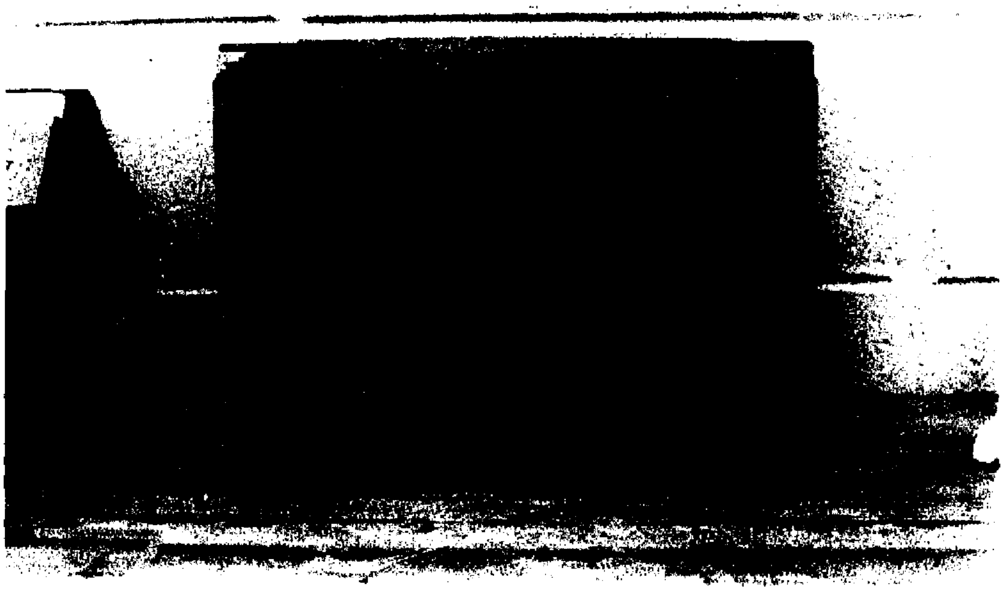

Fig. 4. Front view of response box with superimposed grid.

The stimulus source consisted of individually housed, incandescent light bulbs (CM 313, T-3-1/4) located directly behind each target. Intensity was attentuated via a resistor, so that only a faint orange-yellow glow could be perceived at the target site by a human observer, with essentially no illumination of the surround and no afterimages. The luminance of the target appeared equally bright to a 0.78 mL light source as measured by a Macbeth Illuminometer. Except for the first target of a series, all targets were pulsed electrically for 100 millisec as measured by an electromechanical timer (Standard, accurate to 10 millisec). This measurement was used throughout the experiment since it was not practical to make light duration measurements daily. A radiometer (EG & G 580/585) was used on one occasion to measure light duration which was then displayed on an oscilloscope. The radiometer was fitted with a photometric filter to equate the sensitivity of the instrument to the sensitivity of the human eye. The following measurements were obtained:

1) Delay time measured from the command signal to 10% amplitude of the waveform - 80 millisec

2) Pulse width measured at 50% amplitude of the waveform - 25 millisec

3) Rise time measured from 10% to 90% amplitude of the waveform - 40 millisec

4) Fall time measured from 90% to 10% amplitude of the waveform - 70 millisec.

In summary, the stimulus duration at 50% amplitude was 25 millisec and maximum luminance was 0.78 mL. These parameters were chosen to minimize the possibility of the monkey visually guiding its limb.

All programming was accomplished with electromechanical programming equipment interfaced with solid state circuitry. The programming equipment was assembled in a room adjoining the experimental room, and closed circuit TV was used to monitor the animal's response and the stimulus presentation. The position of the limb could be monitored only when it was interposed between the stimulus and the camera lens. Although no photometric measurements were made, no light was observable in the experimental room after 30 min of dark adaption by the experimenter.

During pilot experiments, it became evident that the animal would not remove its hand from the surface of the response panel when required to make a series of responses. Instead, the animal would follow a sequence of lit targets by swiping the display surface, thereby touching intervening incorrect targets which were recorded as errors. This problem was eliminated by superimposing a grid above the display surface, so that each target was compartmentalized and separate from all others (Fig. 4). The top of the grid measured 1 in. from the display surface, and the grid bars were made of metal rods encased in rubber tubing having a diameter of 5/8 in.

Procedure

Preliminary Procedure

Pilot experiments were conducted to devise a method to encourage deafferents to execute movements to briefly lit, spatially separated targets without visual guidance. Train- was conducted in darkness and the deafferent was required to touch one or more briefly lit targets to obtain food reinforcement.

It was found that the animal frequently succeeded by holding onto a superimposed protective grid in front of the display, so that, when the target was briefly lit, the monkey received immediate visual feedback since its hand was almost over the target. Other investigators have reported that deafferents established start positions for their response limb just before making a reaching movement (Taub et al., 1966; Bossom & Ommaya, 1968; Taub et al., 1975). Rather than wait for a stable start position to develop spontaneously, the experimenter provided the deafferent with a spatially defined start position. This was the first target which remained lit until the animal touched it (start target). Touching the start target triggered the onset of a second target, lit dimly for a fraction of a sec to eliminate the possibility of visual guidance of the responding limb (see Apparatus section). It was found that the monkey was not able to reach the second target under these conditions. Successful performance was obtained by allowing the animal various amounts of visual guidance during two shaping conditions: 1) permitting the animal to respond in the light and then gradually reducing the light intensity or 2) leaving the target lit for 1 sec and then, on subsequent trials, reducing its duration. However, when in darkness the animal still could not reach the second target, if it was only briefly lit, even after thousands of successful performance of the 2-target task under shaping conditions.

At this point, the possibility was entertained that the visual information provided during the shaping period caused the animal to become dependent upon that source of information without developing alternate mechanisms (presumably central) to perform the task. It seemed necessary to develop a shaping procedure that provided only a brief visual stimulus at the second target position, thus eliminating visual guidance of the responding limb, and forcing reliance on alternate mechanisms.

Various methods were explored and the most successful appeared to be a repetitive pulsing of the lit target (pulsing procedure). The second target was pulsed for 25 millisec at a rate of 2/sec until it was touched, followed by a systematic decrease on subsequent trials in the number of pulses provided. The monkey was able to reach the second target, lit briefly only once, after several weeks of training using the pulsing procedure. It seems unlikely that target pulsing enabled the deafferent to guide its limb visually, but it did provide visual information as to when its hand was over the correct target. The pulsing procedure became the training technique used in this experiment. In the course of shaping, a number of steps were followed which are described below.

Final Procedure

At the start of training, each animal was chaired and the left limb was restrained. The animal was shaped to reach with the right limb in order to grasp and bring food to its mouth. The response panel and the food pellet dispenser were then mounted on the chair.

Since there were two chairs and three deafferents, the following three week sequence was used for each animal: first week, chaired continuously; second and third weeks alternating between chaired for one day and chaired for the one-hour experimental session. When remaining in the chair for one day or longer, the left arm was released after testing and an extension of the neck board was interposed to prevent the animal from viewing its limbs or bringing them to its mouth. Food supplements were given after each session, and the animals were maintained on a 23 hour food deprivation schedule. Water was available except during the session. Sham operates were operated last, therefore they were tested after deafferents had completed all testing.

Targets were numbered 1 through 9 starting with the upper left target (1), moving left to right, and ending with the bottom right target (9). Each animal was shaped to reach forward and touch target 1 in order to receive a food pellet. On each trial, the light behind target 1 was lit for 7 sec or until the monkey touched it. There was an intertrial interval of 3 sec. The experimental room was dark, but the animal was able nevertheless to view its moving limb since the amount of light shed by target 1 was sufficient to allow the animal to use visual guidance. During the early stages of shaping, the experimenter moved the animal's arm to target 1. Later, a food pellet was taped over target 1 to induce the animal to reach for it, thereby triggering the delivery of a pellet from the hopper. When the animal achieved proficiency at touching target 1, its luminance was reduced to 0.78 mL. For the rest of the experiment, the monkey responded without visual guidance of the moving limb after touching target 1.

After attaining proficiency in reaching target 1, monkeys were shaped to perform 2- and 3-target tasks. For the deafferents the first target (1) remained lit until touched (start target) followed by the lighting of a second target. (Sham operates were able to perform tasks without a start target). A trial was initiated by touching the start target. A correct response occurred when the animal touched each target consecutively within 8 sec for a 2-target task or 10 sec for a 3-target task. An error was defined as touching any target other than the lit targets. Specific errors were recorded for each task throughout the experiment. A correction technique was used: if, after an error, the correct target was touched within the alloted time the monkey received a reinforcement. There was an 8 sec intertrial interval.

Two methods were used to encourage responding. The first involved an occasional "free" reinforcement, and this method was used when determining whether deafferents would succeed in touching the second target when it was lit briefly (25 millisec) only once. A block of 25 trials was given for this purpose and the "free" reinforcement delivered only when the animal had motor difficulties, e.g. errors. Otherwise, reinforcement was delivered only after the animal touched the second target in sequence. There was little or no response to the second target during a block of 25 trials, and a second method was employed whereby the second target was pulsed at a rate of 3/sec for periods of up to 8 sec or until the animal touched it. The pulse rate was then reduced systematically to 3/sec, 2/sec, 1/sec, .67/sec and .5/sec; and finally only a single pulse was delivered. Criterion of learning at each pulse rate and throughout the experiment was 24 correct responses in a 30 trial block, except for the shaping tasks given to deafferents where it was 40 correct responses in a 50 trial block. Preliminary data on such tasks showed that a large number of blocks would be needed for deafferents to reach criterion; therefore, an increase in the number of trials per block would not mask any information. When criterion was achieved on a block of trials the next pulse rate began. To complete a task the criterion had to be achieved on two consecutive days with the second target pulsed only once. An average of seven blocks of trials was given to deafferents during each 1 hour session, while sham operates received an average of 11 blocks for the same time period. Deafferents were trained 7 days/week, approximately 1 hour/day. The order of the tasks presented to each monkey is shown in Table 1.

Two target tasks 1-6 and 1-8 were used as shaping tasks to teach the animal to respond to a briefly lit target. Once they had learned to perform these individual tasks, they were required to alternate between these two tasks presented in random order. This was done to insure that deafferents were not just responding to a previously learned location.

In order to test the hypotheses that deafferented animals could reach a second location from any start position once they had learned the location of the second target by its repetitive pulsing, animals were tested on three 2-target tasks. Each series consisted of a training task followed by two test tasks having different start targets but identical second targets. In summary, the following series of 2-target tasks were used (Training and Test Tasks in Table 1):

Series A) 1-9 followed by 2-9 and 4-9
Series B) 1-3 followed by 4-3 and 8-3
Series C) 1-7 followed by 2-7 and 6-7

The three series were presented to all animals in the order A,B,C, so that data on the number of blocks of trials to criterion were comparable among animals. It should be noted that a start target used in one task was never used as a second target in a subsequent task and vice versa, thus retaining novelty of target positions from one task to the next. At the end of each series, criterion level of performance was re-established for all training tasks (i.e. 1-9, 1-3 or 1-7). The question is raised whether deafferents were dependent upon visual information from the briefly lit second target to perform the response. After criterion level of performance was re-established, blocks of 30 trials were given in which 25, 50, 75, 90 and 100% of the trials occurred without the second target being lit, until the animal could touch that target on 24 of 30 trials. The animals were then retrained on each training task after which they were trained to touch second target 3, 7 or 9 presented in random order after start target 1 (Random Training Tasks on Table 1).

TABLE 1

ORDER OF TASKS FOR EACH MONKEY

1	2	3
4	5	6
7	8	9

		Deafferents			Sham Operates	
Procedure		E	F	G	H	I
Shaping Tasks		1-6 1-8 1→6 or 8	1-8 1-6 1→6 or 8	1-6 1-8 1→6 or 8	1-6 1-8 1→6 or 8	1-6 1-8 1→6 or 8
Training and Test Tasks	Series A	1-9 4-9 2-9	1-9 4-9 2-9	1-9 2-9 4-9	1-9 2-9 4-9	1-9 4-9 2-9
	Series B	1-3 4-3 8-3	1-3 8-3 4-3	1-3 8-3 4-3	1-3 4-3 8-3	1-3 4-3 8-3
	Series C	1-7 6-7 2-7	1-7 2-7 6-7	1-7 2-7 6-7	1-7 2-7 6-7	1-7 6-7 2-7
Randomized Training Tasks		1→3 or 7 or 9	1→3 or 7 or 9	1→3 or 7 or 9	1→3 or 7 or 9	1→3 or 7 or 9
3-Target Tasks		1-9-3	1-9-3	1-9-7		
Additional Random Tasks		9→1 or 3 or 7 9→1 or 2 or 4 9→5 or 6 or 8 9→4 or 6 or 8 9→1 or 5 9→7-3 or 3-1 or 1-7			9→1 or 3 or 7 9→7-3 or 3-1 or 1-7 1,3, 7 &9 presented in 7 different sequences	

→) indicates temporal relationship between targets. Target before arrow
-) and dash is start target; targets following arrow are presented in random order after the start target.

Three measures of performance were collected. The first was the number of blocks of trials to meet criterion on each task. The second was the latency of the response defined as the time to the nearest .01 sec for the monkey to reach and touch the second target from the start target. This time was obtained for the following selected movements: horizontal, 1-3; diagonal, 1-9, and vertical, 1-7. Mean latencies were determined from a sample of 100 consecutive trials after criterion had been reached. The third measure was the sum of errors (touching a target other than the start target) for each location for each block.

As seen in Table 1, several additional tasks involving other movement patterns were given in order to delineate further the degree of motor proficiency demonstrable by deafferents. These tasks ranged from two that involved a sequence of three targets (1-9-3, 1-9-7) to one that involved randomization of three target tasks (9→7-3 or 3-1 or 1-7). Tasks of intermediate difficulty were given to deafferents, in order to facilitate training on other tasks. Included were 2-target tasks for which the second targets were adjacent to a previously learned second target (9→1 or 2 or 4) and half the distance from the start target (9→5 or 6 or 8) in comparison to the original 2-target tasks given in series A, B and C. These tasks were then presented together with those learned earlier, thus varying the extent of movement required in one direction (9→1 or 5) and in multiple direction (9→4 or 6 or 8).

In order to establish that the limits of motor performance were not yet approached for the sham operates, a 4-target task was presented using all four corner targets (1,3,7,9) presented in seven different 4-target sequences. For all tasks given to sham operates, the first target was equated in brightness and duration to the subsequent targets, since they did not require a start target to respond.

On task 9→1 or 3 or 7, a recording was made of the frequency and location of errors for every trial. An analysis of errors was made in order to determine whether monkeys made consistent responses to particular second targets instead of to the signalled target. Repetitive responses on the same target within a given trial, whether they were correct or incorrect responses were also noted. On all other tasks, errors were recorded for each target only at the end of a block of 30 trials; therefore, a differentiation between consistent, repetitive or intertrial response errors could not be made.

Deafferents were observed in their cages with the helmet on and in a free situation without the helmet. Their ability to climb, ambulate, grasp and make visual placing responses were recorded. One deafferent (F) was observed in the free situation while blindfolded. Skin sensitivity was tested via pin-prick, hair tugging, and skin pinching in an effort to detect any recovery of sensation in the deafferented limbs.

CHAPTER III

RESULTS

The deafferents had great difficulty coordinating movements of their forelimbs to direct them toward food crackers placed in the animals' visual field. In each case, the experimenter had to lift the limb from the elbow until the animal saw its hand. Only then did the monkey make an attempt to move the limb. One to two weeks of training were necessary before the animal would raise its limb, direct it accurately toward a cracker, grasp it and bring it to its mouth. The monkey was then trained to perform similar reaching movements toward the response panel. Deafferents and sham operates always succeeded in reaching the start target. It was noted that, even after considerable training, the responses made by deafferents were not of the smooth, direct nature of those seen in the sham operates. Instead, the limb was raised, the elbow flexed and the hand thrust toward the target.

Performance data are presented separately for each animal in Fig. 5-11. Successive figures represent a particular stage of the experimental procedure and are presented in chronological order. The figures show the number of blocks of 30 trials to criterion for each animal on a particular task, except for Fig. 5 where blocks of 50 trials were used for deafferents.

The ordinate scales on Fig. 5 are different for the two groups of monkeys since 50 trials per block were used for deafferents and 30 trials per block were used for sham operates. However, the scales are proportionate to one another, so that direct comparisons can be made between animals. Deafferents required 350-5050 trials using the pulsing procedure before they performed each shaping task at criterion. Sham operates required comparatively little training, 30-210 trials, so that, by the second or third shaping task, one block was often sufficient to achieve criterion. None of the animals required more blocks of trials to reach criterion on the two tasks presented randomly in comparison to the number of trials required to learn them separately. Deafferents required 350-1100 trials to learn the randomly presented tasks; whereas, sham operates required only 30 trials.

Performance on each of the three series of 2-target tasks is shown in Fig. 6, 7 and 8. The figures show that, after learning the training task, all animals reached criterion on the first and second test tasks, usually on the first block. There were substantial savings in the number of blocks needed to achieve criterion between the first training task and the remaining two, i.e., among first tasks, training 1-3 was the easiest for the deafferents to learn, requiring the fewest number of blocks. Training on 1-9, 1-3 and 1-7

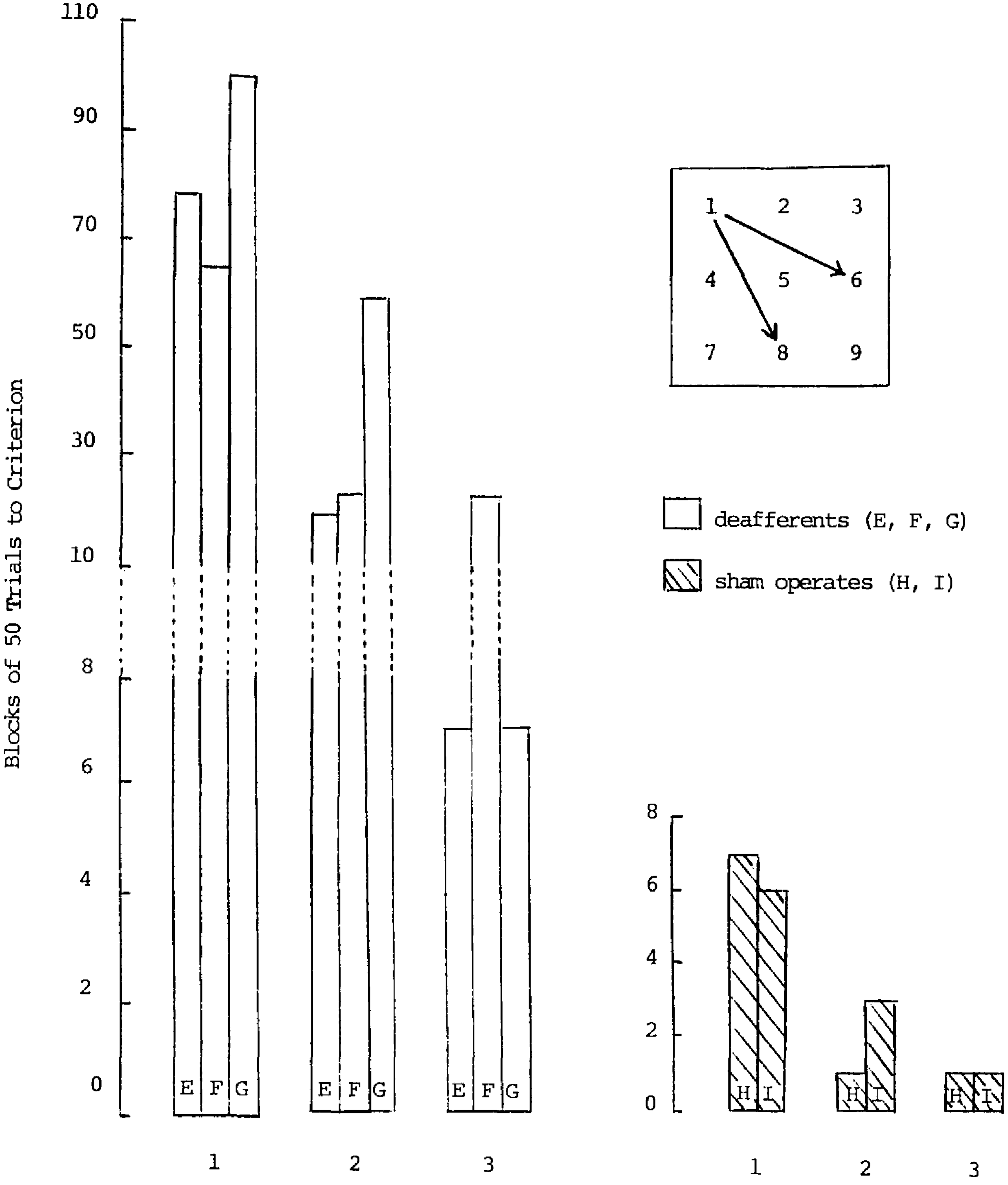

Fig. 5. Performance on 2-target tasks: Shaping. (1 - first task, 1-6 or 1-8; 2 - second task, 1-8 or 1-6; 3 - third task, 1→6,8.)

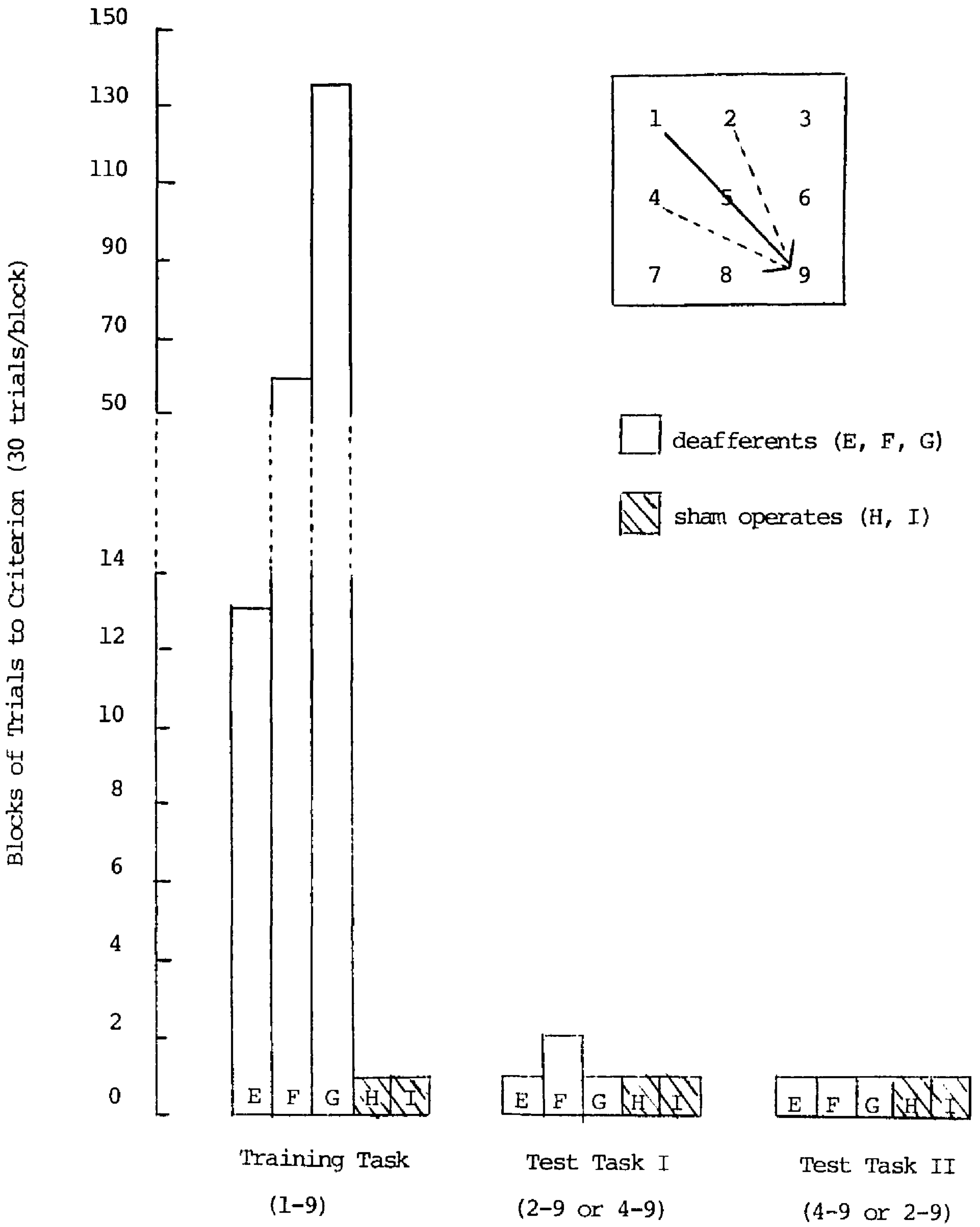

Fig. 6. Performance on series A, 2-target tasks: Touching target 9 from various start targets.

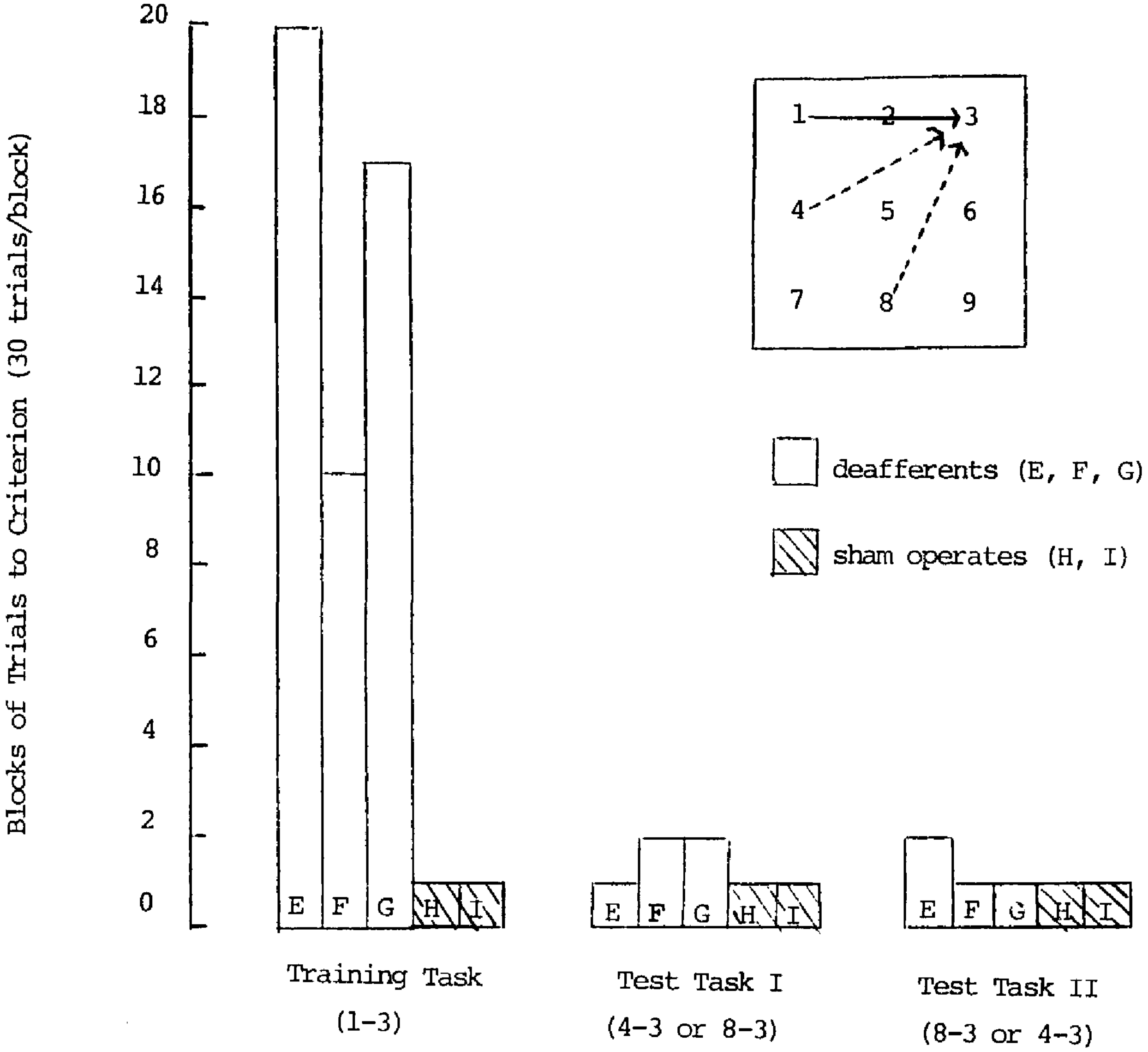

Fig. 7. Performance on series B, 2-target tasks: Touching target 3 from various start targets.

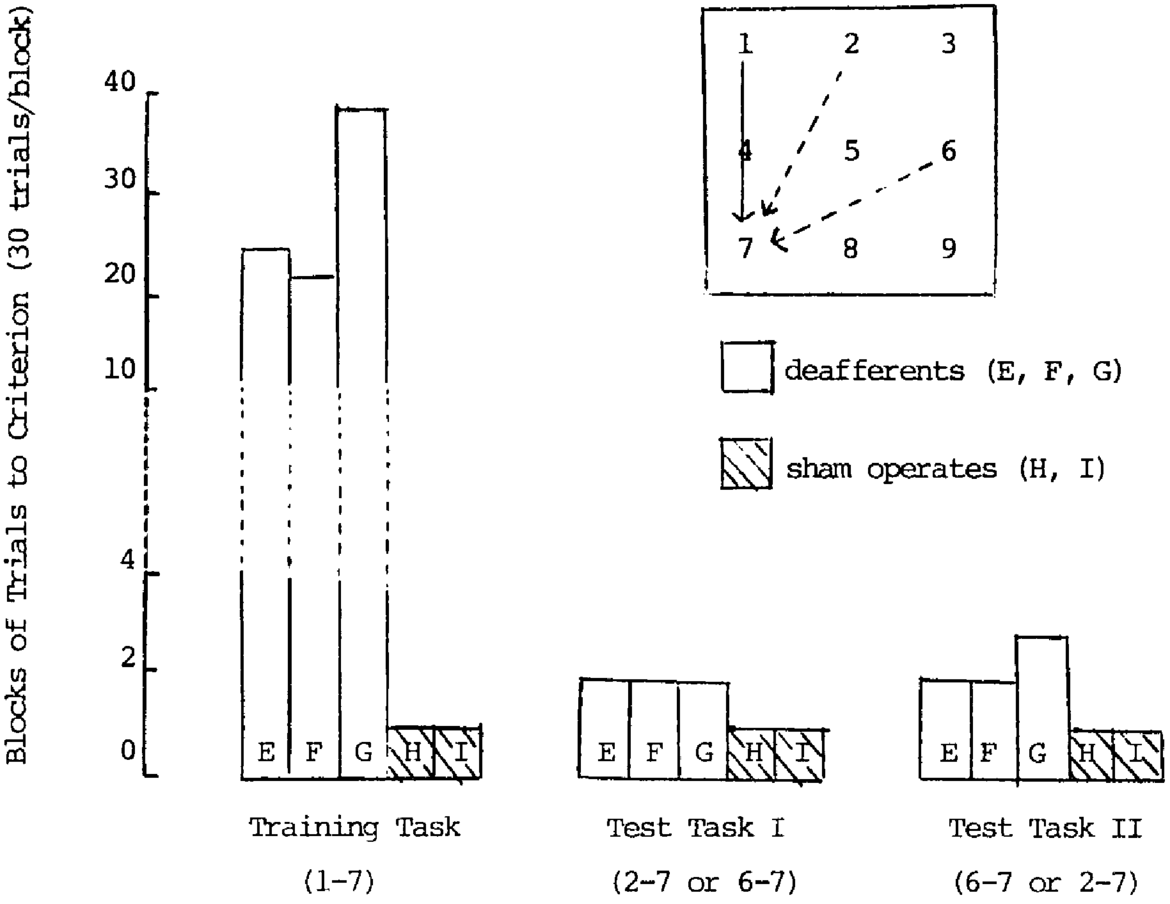

Fig. 8. Performance on series C, 2-target tasks: Touching target 7 from various start targets.

required an average of 69, 16 and 28 blocks respectively. Sham operates reached criterion on the training tasks on the first block. Recall that after re-establishing performance on each training task at the end of each series, deafferents were tested without the second target being lit. On those trials, they needed an additional two to seven blocks to learn to reach for the second target. Monkey F, however, required 26 blocks to perform this task on the sequence 1-9.

A comparison of Fig. 6, 7 and 8 with Fig. 5 reveals that, overall, deafferents required fewer trials to reach criterion on the training tasks than was the case for the shaping tasks. These data might be interpreted to mean that two deafferents showed a transfer effect between the performance on the shaping tasks and the training task in series A. Monkey E benefitted from the prior learning of 1-6 and 1-8 as seen in the performance on 1-9. Monkey G made response errors by touching 6 before touching 9 when performing 1-9. AS a result, 13 blocks were necessary for E to achieve criterion, while 133 blocks were required by G. The percent correct responses on the first block of trials given to each monkey on the tasks in these figures is shown in Table 2. In all possible comparisons, deafferents showed better performance when start targets were changed, as in tasks 1-9, 4-9, 2-9, than when second targets were changed, as in tasks 1-9, 1-3, 1-7. Sham operates showed good performance on all tasks.

Fig. 9 shows that all animals required relatively few

TABLE 2

PERCENT CORRECT RESPONSES ON FIRST BLOCK OF TRIALS WHEN START AND SECOND TARGETS WERE CHANGED*

Order of Presentation	Task	Deafferents			Sham Operates	
		E	F	G	H	I
1	Training 1-9	20	4	8	93	83
2	Test 4-9	97	57			97
	2-9			90	80	
3	4-9			93	87	
	2-9	83	87			93
4	Training 1-3**	0	0	16	93	93
5	Test 8-3		73	37		
	4-3	83			90	87
6	8-3	60			87	83
	4-3		83	90		
7	Training 1-7**	0	0	0	90	87
8	Test 6-7	57				83
	2-7		53	47	87	
9	6-7		67	40	87	
	2-7	63				93

*Task 1→6 or 8 was given to all animals prior to the presentation.

**Prior to presentation of training task 1-3, each monkey was reconditioned to criterion on task 1-9; likewise, monkeys were reconditioned on task 1-3 before they were presented with training task 1-7.

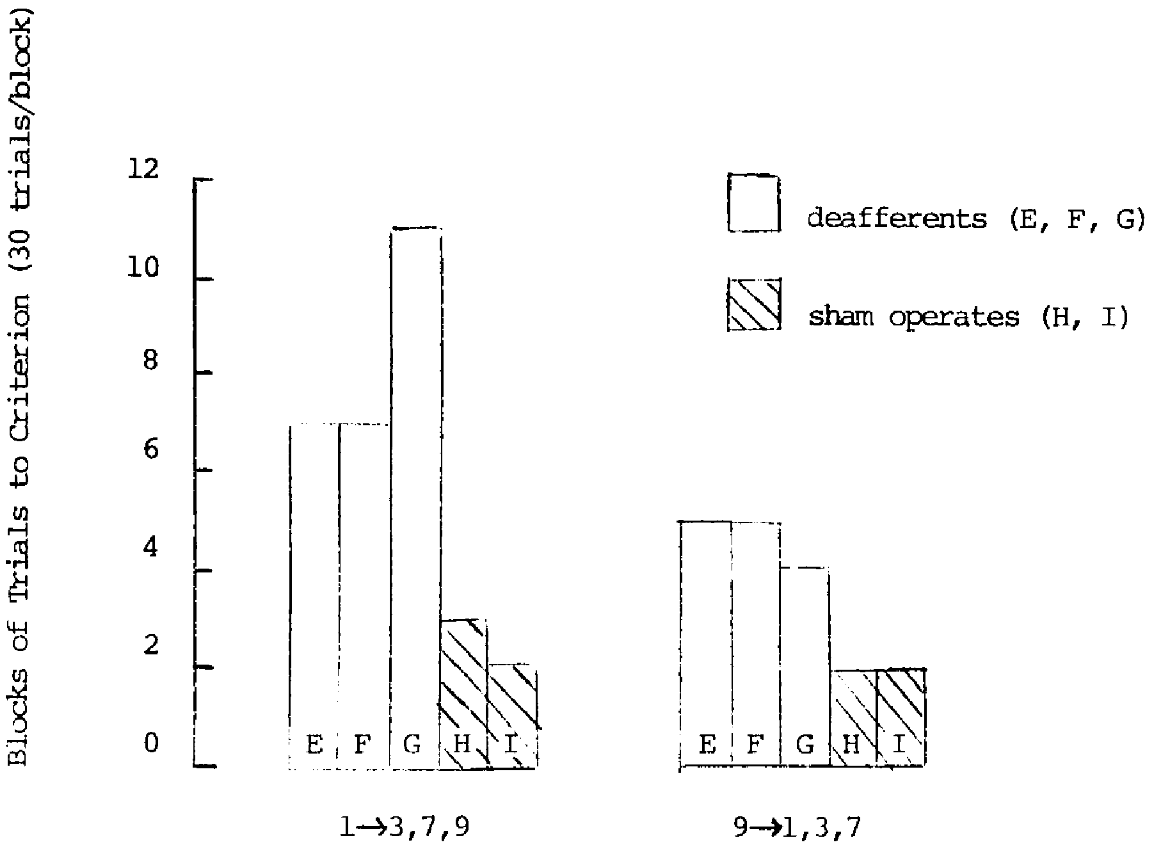

Fig. 9. Performance on 2-target tasks presented randomly.

blocks to perform 2-target tasks presented randomly. Deafferents required 5-11 blocks while sham operates required 2-3 blocks. Changing the start position did not result in any increase in the number of blocks needed to reach criterion.

In comparison to the number of blocks to criterion for the shaping tasks and the training tasks in series A, B and C, relatively few blocks were required for each of the tasks shown in Fig. 10. Deafferents learned to perform a 3-target task with less difficulty than the original learning of a 2-target task. They showed little difficulty reaching criterion on the following tasks: 1) from a start position to new second targets which were adjacent to a previously learned second target (9→1 or 2 or 4), 2) to second targets located half the distance from the start target in comparison to the 2-target tasks given in series A, B and C (9→5 or 6 or 8) and 3) to second targets located at different distances from the start target (9→4 or 6 or 8). One deafferent displayed some difficulty learning to respond to second targets both located in the same direction from the start target (9→1 or 5).

Fig. 11 shows that an average of 14 blocks of trials were needed by deafferents while only two blocks were needed by sham operates to learn to perform three, 3-target tasks presented randomly. Before these tasks were presented randomly to deafferents, they were presented to criterion in the following order: a) as fixed 3-target tasks in blocks of 30 trials each, b) as fixed 3-target tasks in groups of 5 or 10 trials within a 30 trial block, and c) as three 3-target tasks presented randomly

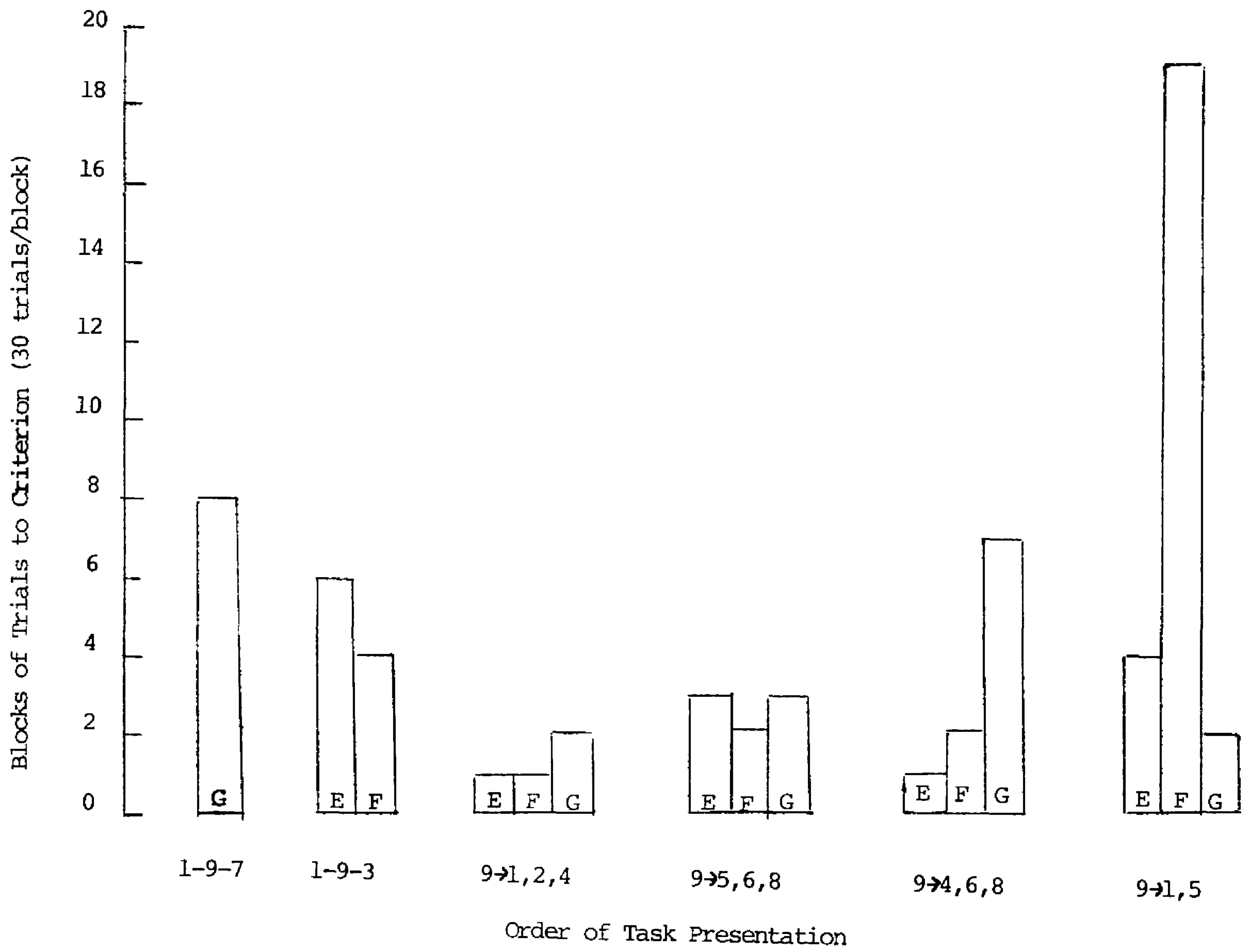

Fig. 10. Performance of deafferents on a variety of tasks.

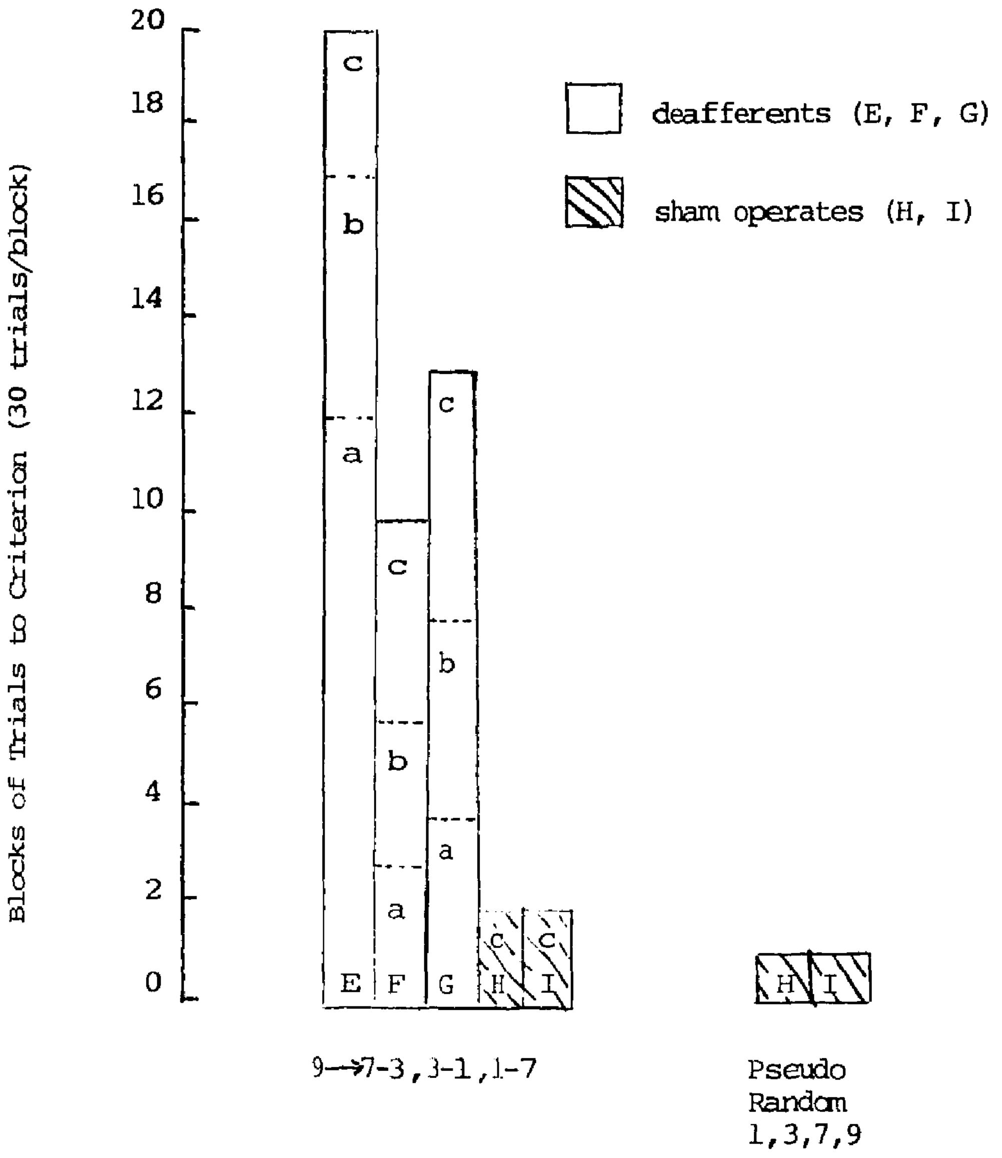

Fig. 11. Performance on final tasks given to each group. a - 3-target tasks presented separately per block. b - 3-target tasks presented separately in groups of 5 or 10 trials within a block. c - 3 target tasks presented randomly.

within a 30 trial block. Sham operates achieved criterion on the pseudo-random sequence of four targets on the first block.

Table 3 shows the marked difference between the two groups of animals on the number of sessions required to reach criterion on each procedure throughout the experiment. Shaping to target 1 as a start position was somewhat different for each deafferent. Fourteen sessions were spent training monkey E to touch target 5 lit briefly only once since, at that time, it had not been decided to use a start position. As the animal showed no evidence of learning, the attempt was abandoned. During the next session, target 1 remained lit until the monkey touched it, and criterion was achieved very rapidly. Monkey F had a great deal of difficulty reaching target 1, so the animal was trained first to respond to target 5 then to target 2 and finally target 1. This method of approximation enabled monkey F to reach target 1 after 21 sessions. Five sessions were required for monkey G to learn to touch target 1.

Animal G required more sessions than animals E or F to learn the 2-target shaping tasks and the training tasks in series A, B, and C, but deafferents required a similar number of sessions for the additional tasks in the experiment (Fig. 9, 10, and 11). The total number of sessions to complete the experiment did not differ greatly among them. It should be noted that the pulsing procedure was used on the shaping and training tasks only for deafferents. Both sham operates performed each procedure in one session completing the entire experiment in four sessions.

TABLE 3

SUMMARY: SESSIONS TO CRITERION FOR EACH PROCEDURE

	Deafferents			Sham Operates	
Procedure	E	F	G	H	I
1-target shaping	15	21	5	1	1
Sum of two, 2-target shaping tasks	33	29	40	1	1
Sum of three training tasks (1-9, 1-3, 1-7)	24	28	34	< 1	< 1
Sum of test tasks (2-9, 4-9; 4-3, 8-3; 2-7, 6-7)	< 2	< 2	< 2	< 1	< 1
Sum of additional tasks (Fig. 9, 10, and 11)	13	13	12	1	1
Total (approximate)	87	93	93	4	4

Figure 12 shows the latency of the response for each animal on three different 2-target tasks. Latency for deafferents decreased from tasks 1-9 to 1-3 and increased slightly from tasks 1-3 to 1-7; sham operates showed little fluctuation among the three tasks. A number of conclusions were drawn from an analysis of variance of mean latencies (Table 4). Although deafferentation did not significantly affect latency at the .05 probability level, the trend was for deafferents to be slower than sham operates ($\underline{p} < .08$). There were no overall differences from task to task in latency; however, there was a significant difference from task to task in latency between deafferents and sham operates ($\underline{p} < .05$).

Statistical tests performed on the variances for each monkey on each task (Table 5) showed the following: 1) deafferents were significantly more variable in latency over all tasks than sham operates F (24,120) = 43.68, $\underline{p} < .001$, and 2) deafferents were significantly more variable in latency on each individual task than sham operates: 1-9, $\underline{F}$ (24, 120) = 72, $\underline{p} < .001$; 1-3, $\underline{F}$ (24, 120) = 21.7, $\underline{p} < .001$; 1-7, $\underline{F}$ (24, 120) = 20.7, $\underline{p} < .001$.

Errors associated with second targets expressed as percent of total trials on task 9→1 or 3 or 7 are shown in Table 6. It should be noted that the percentage was based on total number of trials to criterion for each group--150 trials for deafferents and 60 trials for sham operates on each second target presented randomly in blocks of 30 trials. Errors less than 1% of the total trials for each group were not included. Deaf-

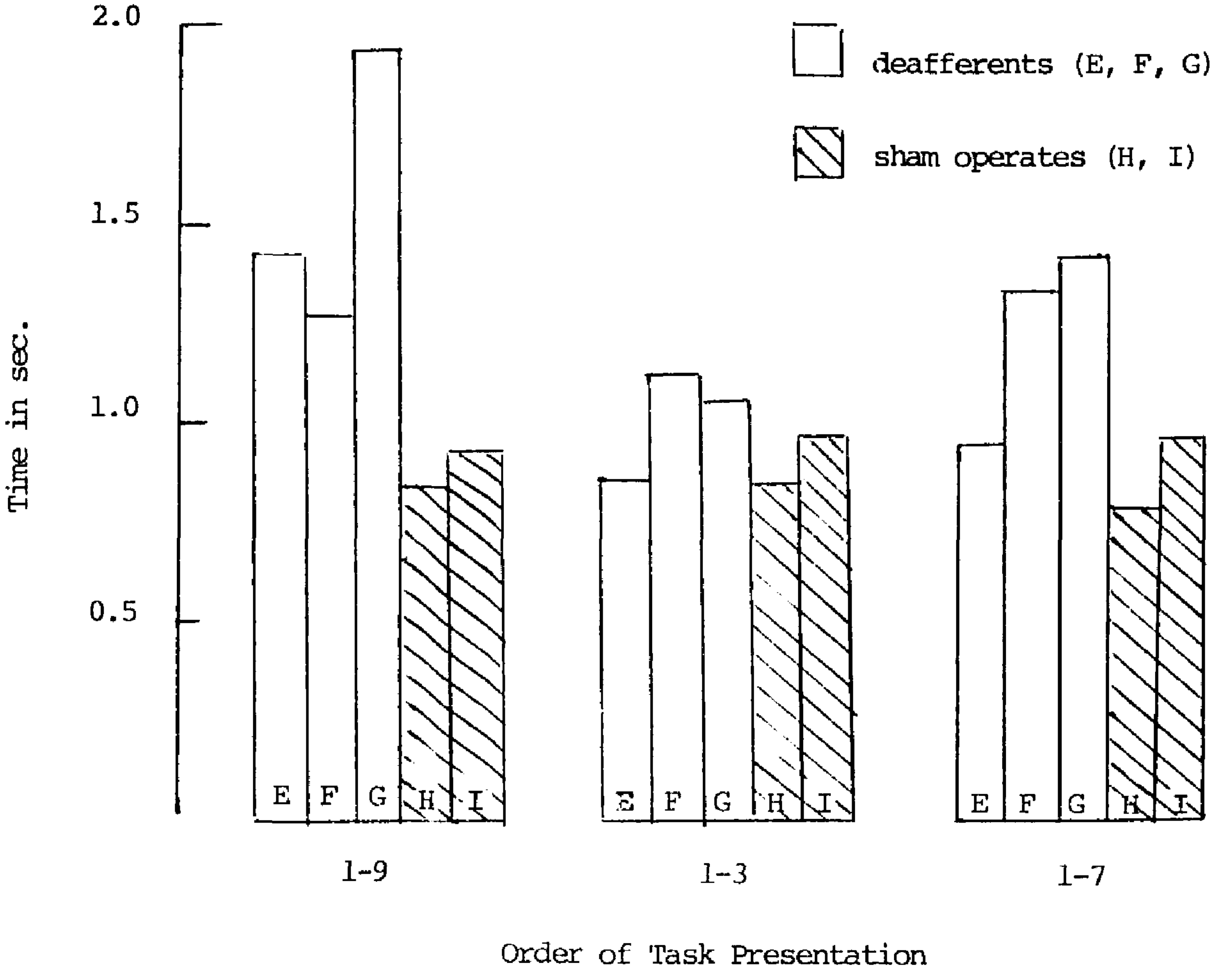

Fig. 12. Latencies of responses for three 2-target tasks. Each bar represents an average of 100 measurements.

TABLE 4

ANALYSIS OF VARIANCE OF MEAN LATENCIES

Source of variation	Sum of Squares	df	Mean Square	*F*	*P*
Between subjects	8490	4			
Condition (deaf. vs. sham op.)	5856	1	5856	6.67	n. s.
Error b	2634	3	878		
Within subjects	5824	10			
Tasks	2606	2	1303	1.81	n. s.
Tasks x Conditions	7540	2	3770	5.24	$< .05$
Error w	4322	6	720		
Total	14314	14			

TABLE 5

INDIVIDUAL VARIANCES OF LATENCIES ON EACH TASK

	Monkey	TASK		
		1-9	1-3	1-7
Deaf.	E	5461	462	466
	F	3655	2354	2895
	G	8752	2088	838
Sham Op.	H	54	73	54
	I	111	38	81

TABLE 6

ERRORS ASSOCIATED WITH SECOND TARGETS EXPRESSED AS PERCENT OF TOTAL TRIALS* ON TASK 9→1 or 3 or 7

	Second Target					
	1		3		7	
Group	Error Target	Percent	Error Target	Percent	Error Target	Percent
Deaf-ferents	2	25	6	13	4	31
			2	9	5	15
Sham Operates	5	4			4	18
					8	5

* 150 trials for deafferents, 60 trials for sham operates.

ferents made error responses to target 2 when they were supposed to touch target 1, and to target 4 when they were supposed to touch target 7. Sham operates made comparatively few error responses, although, they also tended to touch target 4 when they should have touched target 7. It should be noted that 50% of the errors made by the deafferents and 57% of the errors made by sham operates were followed by the correct response within the same trial. Also, over the 150 trials given to deafferents, the total number of errors systematically decreased from an average of 13 on the first 30 trials to an average of 6.3 on the last 30 trials. Most repetitive responses on the same target occurred on the correct target for both groups of animals.

Deafferents were tested for recovery of untrained sequential movements toward the end of the experiment. It was noted, when these animals were placed in a free situation without the helmet, that they failed to ambulate. When prodded they either fell, locomoted backwards or leaped forward using the hindlimbs only. They often fell forward on top of a cracker placed in front of them. In a short time, they used their hindlimbs to grasp the cracker. Within their cages and while wearing the helmet, they were not observed climbing or using their forelimbs to ambulate. Movement in the cage was performed with their hindlimbs, while the forelimbs were used as props to maintain balance in a sitting position. Thumb-finger opposition was not observed. The operated animals displayed the characteristic posture of a deafferented forelimb—forearm slightly flexed at the elbow, and the hand flexed 90 degrees at the wrist. As a result, the dorsal aspect of the hand was in direct contact with the floor of the cage supporting any weight exerted on the forearms. Occasionally the right forelimb was used to push the helmet closer to the animal's mouth, so that it could reach a cracker located inside the helmet. When deafferents with helmets were placed on a vertical wire mesh, they made no attempts to grasp, let alone climb, even when threatened with loss of support. However, after repeating these procedures for a few minutes after each experimental session, they began to use their hindlimbs to support their weight on the mesh while feebly trying to maintain grasp with the right deafferented limb. The forelimbs often became crossed in front of the animal making the monkey unsteady in the sitting position. One animal, monkey F, was blindfolded and observed in the free situation. The animal did not locomote, and when prodded, fell and could not right itself.

The postural characteristics of the hand while making the response was different for each deafferent. Monkey E was the only deafferent that used the finger-tips of the outstretched second, third and fourth fingers to make contact with the target. Monkey F at first used its hand as a fist to make the response and later refined its hand posture by using the dorsal aspect of the second, third and fourth fingers at the last phalangeal joint. Monkey G used the same hand posture as monkey F except that the contact point was the shaft of the middle phalanx near the first phalangeal joint. Sham operates characteristically used the palmar surface of the distal phalanx of the index finger alone or in conjunction with the third and fourth fingers.

Periodic skin sensitivity testing revealed no recovery of sensation in the deafferented limbs throughout the experiment.

CHAPTER IV

DISCUSSION

Taub et al. (1975) trained deafferents to reach spatially separated targets, presented in irregular order, without visual guidance. Since they permitted visual guidance of the responding limb during shaping, the issue raised by the present author was whether visual guidance was actually necessary. The monkeys in the present study succeeded in using their deafferented limb to perform movements to targets presented in random order when visual guidance of the moving limb was excluded during both shaping and testing. Compared to sham operates, however, deafferents were considerably slower to learn each task and showed definite limitations in transferring to tasks involving new second targets. If the start target changed, deafferents continued to perform the task accurately. Exteroceptive and central feedback factors have been suggested to account for the performance by deafferents. Because there are no studies, including this one, that have eliminated all exteroceptive feedback, one cannot say conclusively that central feedback is responsible for the deafferent's success. Caution should be exercised in involving central feedback even if exteroceptive cues were completely eliminated because of the reported existence of ventral root afferents, collateral sprouting, and other residual or regenerated proprioceptive fibers. Several procedures, used in this study, might also be responsible for their performances. These factors cannot be ignored, and they will be considered later. At this point, however, a number of processes will be discussed in exploring the reasons for the performance by deafferents on the tasks used in the present study.

To begin with, exteroceptive feedback, can be subdivided according to the sources of feedback--visual, auditory, tactile, etc. Visual feedback was provided through the use of light pulsing of the second target on shaping and training tasks. This might have provided the monkey with information as to whether its hand was over the correct target. Exteroceptive cues were provided by delivery of the food pellet providing the animal with knowledge of results. Vision, therefore, provided a cue for the limb to respond and verification of a correct limb position, while other exteroceptive cues provided confirmation that a proper limb movement had been executed.

The exteroceptive feedback available to the monkeys in this study would be sufficient to account for the performance of deafferents according to the motor learning theories of Adams (1971) and Schmidt (1975). They theorized that central programs of motor responses (central motor programs) are slowly formed over many trials. The programs are based on stored information of experimental conditions and motor requirements obtained during shaping, and are modulated by knowledge of results and limb position information. Each program is used to generate efferent commands which are themselves stored to be recalled on the next trial and altered if necessary. The stored information of past movements can be modified during the time necessary to make a correct response. Once the response error was small enough not to interfere with a correct response over a number of trials, learning was complete. Looked at that way, in the present study, pulsing the second target gave deafferents visual feedback over a sufficient period of time, and along with knowledge of results, enabled them to determine the response error and to update the record of past movements. Such information could be used to alter the motor response on succeeding trials.

The development of central motor programs as outlined by Adams (1971) and Schmidt (1975) can be elaborated to account for the performance by deafferents on tasks involving reaching from start targets to new second targets. Following their theory, it is hypothesized that deafferents initially need some minimal amount of feedback relative to limb position (e.g. via pulsing). The present author postulates that the visual information is used to form, first, a central representation of a particular target's location and then an appropriate central motor program. Once this is established, the monkey can manually locate that target from any start target without visually guiding the limb. The start target is employed in this study to inform the deafferent of the initial position of its limb. Later, in the course of learning, the briefly lit second target activates its central representation which triggers the appropriate efferent command enabling the limb to locate that target from any start target. It is further assumed that, after considerable training, the central representation of several targets form a perceptual-motor map of their relative locations. When the target is lit and the corresponding point on the map is activated, limb movement is initiated to that target from the start target. Presentation of a new second target would easily be recognized by deafferents utilizing such a map since this new target would not correspond to any of the central representations of previously learned second targets. At the same time, however, it is hypothesized that it would be recognized as spatially contiguous to targets on the map, thereby enabling deafferents to make appropriate adjustments in their efferent commands and effect the correct limb responses to the new second target.

Another explanation for the performance by deafferents is based on the hypothesis that continued practice of a repeated sequence of active movements would lay down a memory trace of that movement. In the present study, for example, response errors to target 6 by monkey G while performing task 1-9 might involve a conditioned movement to a previously learned target, i.e., target 6 in task 1-6. However, it is unlikely that the learning of the 2-target task reflected simply a conditioned movement, as monkey G and other deafferents were able to reach a previously trained second target position from new start target positions. A conditioned movement might have been used by deafferents to perform "training" tasks, but it would not have been sufficient to explain their immediate performance of "test" tasks. Therefore, the memory trace may be of a target location and may or may not include a conditioned motor movement. The present author hypothesizes that deafferents utilized a perceptual-motor map of the relative target locations, possibly with the aid of the pulsing procedure and/or previously conditioned movements. Such a map might also help to explain the relative ease with which deafferents learned to perform 2-target tasks presented in random order.

Deafferents showed considerable savings across tasks when learning to perform 2-target tasks. There seemed to be a limit on such savings when they were required to perform 3-target tasks presented in random order. A considerable amount of training was given on each separate task before they were presented in random order. What may have made the 3-target task particularly difficult was the fact that two different motor programs had to be called upon. The first program had to be initiated after the response to the start target, similar to a 2-target task, and the second after a response to the briefly lit second target.

Exteroceptive feedback and central representation explanations are not mutually exclusive. The suggestion by Jones (1974b) that there is a need for some minimal amount of exteroceptive feedback during initial training in order to give central representation the necessary time for development was supported in the present study by the effectiveness of the pulsing procedure. The inordinate length of time taken by deafferents, in comparison to sham operates, to learn the shaping tasks might be regarded as the time necessary for development of the appropriate central representation in the absence of proprioception. Furthermore, near the end of the experiment, it appeared as though deafferents might have been correcting errors of limb movements by monitoring efferent signals to the limb. A particular example is seen in the data on task 9→1 or 3 or 7, in which the number of errors associated with each second target was recorded. With this task, there was no pulsing of the second targets, and it was the first time that deafferents were presented with 9 as a start target. They were able to learn this task to criterion within five blocks of trials, with a 50% reduction in mean errors from 13 on first block to 6.3 on last block. Furthermore, errors were corrected within the same trial with almost the same frequency as sham operates. Since the second target flashed only once, the correction of these errors by deafferents was made without visual guidance. However, it must again be mentioned that knowledge of results was available when the correct response was made. In summary, it would appear that central monitoring of efferent commands is not sufficient for initial learning without some exteroceptive feedback but may be sufficient for subsequent learning of similar tasks after appropriate central representations have been developed.

A further benefit of the pulsing procedure may have been to assist deafferents in developing central processes to monitor efferent information. In this regard it should be noted that Festinger and Canon (1965) provided evidence of efferent monitoring of eye movements, specifically saccadic eye movements elicited by a light pulse. They demonstrated that, when a briefly lit target is presented to a subject, his eyes are directed to the location of that target, and he knows the position of his eyes more accurately than if he uses his eyes to track the target to the same location. It is hypothesized that the pulsing procedure, as a training technique, allowed the animal very brief glimpses of the second target and elicited saccadic movements. Thus, an appropriate stimulus may have been given for the animal to localize that target within its visual space and to use efferent signals to direct the deafferented limb to the target.

Before entertaining the foregoing explanations of the performance by deafferents one must rule out the possibility of residual or regenerated proprioceptive fibers. Among those possibilities are ventral root afferents, collateral sprouting, regeneration, incompleteness of surgery, and proprioceptive feedback from head movements and intact body areas.

The functional significance of sensory nerve cells and fibers in ventral roots has yet to be ascertained. Any experimenter who wishes to entertain a central feedback theory may have to consider the significance of ventral root afferents. If in fact they were present and viable, they could not be found on sensory examination. In this study, deafferents were tested neurologically on a periodic basis and showed no signs of sensory function over a 4-month postoperative period.

It has already been mentioned that denervation hypersensitivity was regarded by several authors as a precursor and possible stimulant for collateral sprouting which, in turn, was considered a possible facilitatory mechanism for the development of central feedback in deafferents (Goldberger & Murray, 1974; Sharpless, 1964). As such, these mechanisms might be responsible for the performance by deafferents. Had a second group of deafferents been allowed to recover for 4-months postoperatively before shaping began for this study, some data bearing on collateral sprouting might have been obtained. Likewise, the same control could have been applied to a study of regeneration. In this study, it is unlikely that regeneration could have occurred in the deafferents since there was resection of a portion of the dorsal roots rather than just transection. This would make it virtually impossible for the stumps to become approximated thereby precluding regeneration.

With regard to incompleteness of surgery resulting in the presence of some residual proprioception, it is well documented that, when either C6, C7 or C8 dorsal root is left intact, there is so much retention of function that the use of the partially deafferented limb appears almost normal (Lassek, 1953b; Twitchell, 1954). However, it is highly unlikely that an entire root could be missed surgically, and it is only remotely possible that a rootlet or even a filament from a rootlet was left intact since the entire area was re-examined under 25 power magnification after surgery was complete. Although the functional significance of leaving a filament of a rootlet intact has yet to be demonstrated, it probably would have been noticed on neurological testing, probably as an area of hyperesthesia. Since no evidence of sensation was found during periodic testing, it was concluded that the deafferentation was complete. To attempt to verify the lesion using standard histological methods would not be convincing since every spinal section might have to be examined from C2 to T3 in order to detect an intact filament. Gross inspection at autopsy was performed but is inconclusive because of the difficulty in differentiating between scar tissue and intact dorsal root fibers.

There are two other proprioceptive feedback sources which deafferents may have utilized. The first is from head movements and the second from other intact body areas. All momkeys were permitted unrestrained head movements in the present study. If proprioceptive feedback from head movements contributes to the performance by deafferents, as suggested by Bossom and Ommaya (1968) and Taub and Berman (1968), then one way to prevent them, when doing deafferentation research would be to clamp the head into a fixed position. This would reduce afferent feedback from labyrinthine stimulation. With saccadic eye movement, however, efferent signals from vestibular nuclei could stimulate the appropriate head turning muscles, and, although the head would not move, these signals might be used to control limb movements. Vestibular nuclear lesions might offer a better means of evaluating this possibility. To eliminate the monkey's reliance on intact body areas one could extend the area of deafferentation caudally at least to the point of removing dorsal root projections to the cuneate and accessory cuneate nuclei. This means a dorsal rhizotomy down to T7 (Shriver, Stein, & Carpenter, 1968), T8 (Walker & Weaver, 1942) or even as far as L1 (Carpenter, Stein, & Shriver, 1968). However, increasing the extent of deafferentation may only eliminate the more obvious somatic areas which may be influenced by limb movements. It has been suggested that monkeys may learn to pair two simultaneous efferent signals--one to a deafferented limb and the other to some remote but innervated body part, such as the jaws (Bossom, 1974). In this way, some modulation of deafferented limb movements might be possible via sensory feedback from an intact body part.

In attempting to explain the performance by deafferents, post-operative care and significance of using a start position during training and testing must be considered. The role of postoperative care in the recovery of function in deafferents, has been stressed by several authors. For a review of some of the techniques used, see Bossom, 1972, 1974; Gianutsos, unpublished dissertation, 1975; Taub et al., 1972b, 1973. Other researchers have noted the importance of postoperative care, rehabilitation and training techniques for maintaining the integrity of neural elements related to functional recovery following spinal cord transections in man (Asratyan, 1963) and in rats (Freeman, 1955).

In the present experiment, postoperative care was primarily directed toward maintaining the integrity of the fingers because the monkey had to make contact with a target which could only be activated by the flow of current through the skin of the fingers touching the metal screening over the target. Any scars, scabs or callosities of the skin area used to contact the target might therefore impede current transmission and delay triggering of the touch-activated mechanism.

In order to safeguard the fingers from the most prevalent source of damage, self mutilation by biting, deafferents wore helmets at all times when not in the restraining chair. Since food and water were available without the monkey having to use its forelimbs, the monkey received encouragement to use them only during the 1 hour per day experimental session. Gianutsos (unpublished dissertation, 1975) allowed his monkeys to feed themselves by reaching for, grasping and bringing food to their mouths after each experimental session and before he helmeted them. The animals in the present study were also trained to feed themselves but only while being restrained in the chair until they could visually guide their limb to procure food which took 1 to 2 weeks.

Without encouragement to use their forelimbs in the free situation, the deafferents in this study were unable to climb or locomote properly when tested for sequential movements near the end of the experiment. With a short period of experience, however, a slight improvement was noticed on such coordinated movements. These findings reinforce the opinion expressed by many researchers that deafferents must be encouraged through postoperative caring and specific conditioning to regain functional use of the affected limbs (Taub & Berman, 1968; Bossom, 1972, 1974; Taub et al., 1973).

The importance of providing the monkey with a start position was aptly expressed by Bossom (1972) when he said that "it may be that the movement is not completed because the animal does not know where his limb is at the start of the movement and so programs an inappropriate muscular extension that cannot be carried out" (p. 250). In this experiment, preliminary work with two deafferents (pilot monkey and monkey E) showed that for at least 14 sessions neither monkey was capable of reaching and touching a briefly lit target in darkness. Others have shown that deafferents will adopt a systematic start position spontaneously. Several methods used by deafferents to achieve a start position were described by Taub et al. (1966, 1975), such as 1) a rapid movement of the head and body to bring the limb into the same start position before each trial, 2) limited movement after a trial, so that the limb falls back into the same start position, or 3) a striking of intact areas of the body with the deafferented limb providing the animal with sensory feedback as to the limb's location. Other researchers have noted similar behavior by deafferents. Bossom and Ommaya (1968) observed that deafferents would strike their chest with the arm, just before making a reaching movement, when the limb was passively displaced. Liu and Chambers (1971) also passively moved the deafferented limb before the monkey made a learned limb movement and found that the monkey missed the target. However, when the animal was allowed to repeat the movement, it first dropped the limb and adducted it against its chest and then made the correct movement. They concluded that the animal "knows the start position of his limb, keeps up with his motor discharges by central feedback and has an intact body image" (p. 285). In this study, monkeys were given a starting limb position by keeping the first target lit until the animal touched it. The purpose of this was to save training time by not requiring the animal to determine the initial position of its limb.

Throughout, it has been emphasized how successful deafferents performed on the tasks presented in this study. However, there were differences in response latency between deafferents and sham operates. Although deafferents were significantly slower in the time required to move the deafferented limb from a start target to a briefly lit second target when compared to sham operates, the faster response latencies of deafferents occasionally overlapped the slower response latencies of sham operates. This contributed to the lack of a large difference in the mean response latencies between the two groups of monkeys. In contrast, the two groups differed enormously in variance. In explanation, consider the design of the response box. It may be that the deafferent moved its limb from the start target to the second target almost as rapidly as the sham operate but then had significantly greater difficulty thrusting the hand into the correst response compartment to activate the target. During the initial shaping to respond to target 1, it was observed that deafferents, especially monkey F, often had their hands over the correct target but failed to touch it. One way to examine this possibility would be to use a photoelectric beam, invisible to the monkey, to signal to the experimenter the time of arrival of the hand over the target. However, it should also be noted that there are some electrophysiological data which may help to account for these latency differences. Vaughan et al. (1970) compared changes in the motor potential recorded over the hand area of motor cortex during wrist extension in normal and deafferented monkeys. Although the overall waveform of the motor potential remained the same, deafferented monkeys showed significant increases in cortico-muscular delay (time between the start of cortical activity and the start of muscular movement) and EMG latency (amount of time needed for a complete muscle contraction).

CHAPTER V

SUMMARY AND CONCLUSIONS

Deafferentation has been employed by many researchers in an attempt to ascertain the degree to which proprioception is necessary for monkeys to perform purposive movements. Deafferents can be trained to perform such movements provided proper postoperative care and training techniques are utilized. Previous studies indicated that vision is essential, during shaping, for the learning of reaching behavior in deafferents. The purpose of this report was to determine whether deafferents could perform fixed and random reaching movements without visual guidance of the moving limb during shaping and testing.

Deafferents and sham operates were trained to perform responses, without visual guidance, on a task requiring a series of movements between briefly lit, spatially separated, targets. An important procedure in training was pulsing of the second target. Deafferents had to be shaped to perform 2-target tasks involving a new second target. They succeeded in performing on tasks involving new start targets. Once deafferents had learned specific 2-target sequences, they could perform these sequences when presented in fixed and random order, without visual guidance. Later in the experiment, they performed 2-target tasks presented randomly that they had not learned separately before. Sham operates had no difficulty performing any of the tasks given to deafferents. They required shaping only at the beginning of the experiment. It was also noted that response latencies of deafferents were longer and more variable than of sham operates.

Results were discussed in terms of exteroceptive feedback, central motor programs, central representation and conditioned movements. Data were consistent with the hypothesis that a naive bilaterally deafferented monkey uses visual information from the target in order to form a central representation of its location which may then be used to activate a central motor program. The central representation of several targets may evolve into a perceptual-motor map of target locations which could account for the deafferent's ability to reach previously learned second targets from new start targets.

APPENDIX I

COLLATERAL SPROUTING

According to Liu and Chambers (1958), it was not until the development of the Nauta silver staining technique for degenerating nerve fibers that collateral sprouting could be investigated in the central nervous system. These authors observed collateral sprouting in the spinal cord of kittens. They traced the degeneration of a single pair of dorsal roots sectioned adjacent to an area that was unilaterally deafferented 9 months before. Degeneration was considerably more extensive along the axons and at the paraterminal regions of the dorsal root on the partially denervated side. These findings were confirmed and extended by Goldberger and Murray (1974). Spinal cord transection was performed in chronic unilaterally deafferented cats approximately 5 days before sacrifice. Paraterminal degeneration was significantly greater on the deafferented side, especially in lamina IV, base of the dorsal horn and lamina VII (zona intermedia). Lamina III and IX were two regions where collateral sprouting was not observed despite the huge amount of dorsal root degeneration in lamina III. This may be because lamina III does not receive descending projections (Murray & Goldberger, 1974) while lamina IX receives less than 1% of its projections from dorsal roots, with the vast majority coming from segmental propriospinal and interneurons (Gelfan, 1963; Kuypers, 1964).

There is considerable evidence for collateral sprouting in other central nervous system structures. An example may be found in the spaces left by degenerated synaptic terminals in the superior colliculus after enucleation in rats which are re-occupied with new synaptic terminals from intact afferent systems (Lund, R. D. & Lund, J. S., 1971). In another example, enucleation in neonatal rabbits results in collateral sprouting from ipsilateral retinofugal fibers in the superior colliculus (Chow, Mathers, & Spear, 1973). It is interesting to see that terminal sprouting of optic tract fibers in lateral geniculate nucleus occurs in rats after occipital cortex ablations (Goodman & Horel, 1966). Evidence by Lynch, Deadwyler, and Cotman (1973) shows that ablation of the entorhinal cortex in rats results in a significant increase in the number of hippocampal commissural fibers projecting to granule cells in the dentate gyrus. The commissural fibers innervate the inner molecular layer and the outer molecular layer, which formerly received projections only from entorhinal cortex. It was also reported that stimulation of the commissural pathway results in response potentials having similar latencies and wave forms in both molecular layers.

Even if deafferentation caused sprouting, it is questionable if this would be an explanation for recovery of function, as it is not known if sprouting results in the formation of permanent functional pathways for afferent input (Bossom, 1974; Chow et al., 1973; Eccles, J., Eccles, R., & Shealy, 1962; Goldberger & Murray, 1974; Lynch et al., 1973; Murray & Goldberger, 1974; Windle, 1955). In one example, Eccles et al. (1962) studied the effect of partial dorsal rhizotomy on the growth of collateral sprouts. They found that the number of motoneurons from which an EPSP could be recorded intracellularly after muscle nerve stimulation was significantly reduced in partially deafferented kittens. They concluded that the "degeneration of primary afferent fibers in the young kitten does not cause the intact afferent fibers to develop collateral sprouts that achieve functional connections with motoneurones" (p. 557). Several points need to be made concerning this study. Collateral sprouts can be found when a dorsal root fiber or rootlet is left intact as has been suggested by Goldberger (personal communication). Also, collateral sprouting was observed from the spread of degeneration over several spinal segments when a previously spared dorsal root was sectioned in chronically deafferented cats (Liu & Chambers, 1958). Eccles et al. (1962) had hypothesized that since 1/2 - 2/3 of the primary afferents had degenerated, the subsequent large reduction of synapses on motoneurons should stimulate the remaining afferents to produce collateral sprouts and new functional connections. However, relatively few dorsal root fibers project directly onto motoneurons (Gelfan, 1963). Furthermore, Goldberger and Murray (1974) have demonstrated that collateral sprouting occurs primarily from descending spinal pathways in an area previously deafferented. Since these pathways exert an inhibitory effect on the motoneuron via interneurons (Eccles & Lundberg, 1959; Wilson, 1966; Hultborn, Jankowska, & Lindstrom, 1968) a reduced EPSP might be expected after peripheral nerve stimulation. Renshaw (1946) demonstrated in cats and rabbits that many interneurons in the ventral horn do discharge as a result of antidromic stimulation of the proximal stump of a ventral root or of a peripheral nerve whose dorsal root had been sectioned. It is interesting to note that these interneurons have an inhibitory effect on the subsequent firing of motoneurons (Eccles, Fatt, & Koketsu, 1954; Hultborn et al., 1968). Also they most probably are excited by recurrent collaterals from the motor axons (Granit, Pascoe & Steg, 1957). Finally, it has been reported that recurrent collaterals are involved in the antidromic stimulation of motoneurons which inhibit the discharges of other motoneurons innervating the same peripheral nerve (Renshaw, 1941).

The functional significance of sprouting in the recovery of spinal reflexes has been discussed by several authors. McCouch, Austin, Liu, C. N., and Liu, C. Y. (1958) found that dorsal root afferents increased in number ipsilateral to hemisection of the spinal cord in cats and monkeys, which may account for the significant increase in the presynaptic potential recorded from these roots. This was presumably caused by dorsal root axonal sprouting following the loss of suprasegmental influence from descending tracts. This finding led them to hypothesize that the increase of segmental afferent influence over reflex arcs resulted in exaggerated reflexes and concommitant spasticity. Murray and Goldberger (1974) confirmed this finding in the cat after section of the lateral and ventral funiculi on one side. They suggested that collateral sprouting from dorsal roots is responsible for hyperactivity of stretch reflexes. In addition, a specific correlation between sprouting and reflex activity was reported by Goldberger and Murray (1974). They found that "labelled protein is transported in dorsal root axons to the region of the ipsilateral commissural nuclei of transected-deafferented cats in increased amounts at a time when crossed reflexes had become hyperactive" (p. 51).

Goldberger and Murray (1974) and Murray and Goldberger (1974) attempted to isolate the neural system responsible for collateral sprouting after another system was surgically interrupted. They correlated the recovery of motor function with reflex activity and cord degeneration studies to make a case for the functional significance of collateral sprouting in deafferented or partially hemisected cats. They found that only descending reflexes of ipsilateral origin became exaggerated, and their return was closely followed by recovery of motor functions in chronically deafferented cats. Furthermore, hemisection of the cord on the deafferented side resulted in absolutely no recovery of motor function or reflex activity. The same results were obtained when section of the cord was limited to lateral and ventral funiculi. In addition, section of the dorsal funiculi on the side of and at the same time as deafferentation eliminated sprouting from rostral dorsal roots but resulted in the same functional reflex and motor recovery as deafferented only animals. The authors concluded that collateral sprouting occurs selectively from descending tracts on the side of deafferentation.

APPENDIX II

DENERVATION HYPERSENSITIVITY

As an example of denervation hypersensitivity in spinal cats, hypersensitivity of spinal neurons on the side of the lesion to chemical agents has been observed after hemisection of the spinal cord (Cannon & Haimovici, 1939) and after deafferentation (Drake & Stavraky, 1948). In another example, hypersensitivity was found on extracellular recordings from dorsal horn interneurons in cats (Loeser & Ward, 1967). This high frequency activity was noticed two segments above and one segment below an L5 to S1 dorsal rhizotomy ipsilaterally and at the level of the lesion contralaterally. Furthermore, Loeser and Ward noticed that stimulation of an intact adjacent dorsal root caused an evoked response from these interneurons lasting 100 millisec in comparison to 35 millisec from non-deafferented interneurons. The authors noted that any increase in the stimulus intensity caused a sudden jump in the response.

Several researchers have commented on the time course for the development of neuronal hypersensitivity following deafferentation. This is particularly important for deafferentation research since it has been suggested that hypersensitivity might be a stimulant for the development of collateral sprouting which seems to develop concommitantly with the recovery of motor function in the deafferent (Goldberger & Murray, 1974). Hyperactivity of spinal cord interneurons was not seen up to 8 hours following rhizotomy but became fully developed by 14 days (Loeser & Ward, 1967). In this regard, Teasdall and Stavraky (1953) noted that spinal rats did not show neuronal hypersensitivity or a muscular response to corticospinal tract stimulation on the deafferented side for 5 days after deafferentation. Drake and Stavraky (1948) demonstrated hypersensitivity to chemical agents in deafferented neurons 18 hours after the operation at the earliest. They also observed a decrease in muscular response when these same chemical agents were administered soon after deafferentation. These investigators as well as Asratyan (1963) and Goldberger and Murray (1974) have attributed this initial neural and motor unresponsiveness to spinal shock following surgery.

APPENDIX III

VENTRAL ROOT AFFERENTS

Many researchers have reported the presence of nerve cells resembling sensory ganglion cells in the ventral roots of the dogfish, guinea pig, cat, dog, monkey and man (reviewed by Coggeshall, Coulter, & Willis, 1974; O'Donnell & Windle, 1932; Windle, 1931). Sherrington (1894) was one of the early investigators to report that some myelinated fibers were degenerated proximally and some myelinated nerve fibers remained intact distal to a ventral root rhizotomy in the cat and monkey. His observations were confirmed for the dog and cat by Windle (1931), the cat by Mikeladze (1965) and Kata and Hirata (1968), the rat by Dimsdale and Kemp (1966), and the monkey and man by Foerster and Gagel (1933). The presence of unmyelinated fibers in the ventral roots has been reported by several other authors (reviewed by Coggeshall et al., 1974). For example, electron microscopy has shown that approximately 30% of the axons in the ventral root of the cat, frog, monkey and man are unmyelinated and many are found to degenerate proximal to a ventral root section (Coggeshall et al. 1973, 1974).

A number of researchers have provided electrophysiological evidence supporting the presence of ventral root afferents. Lloyd (1941) noted that stimulation of the ventral root in cats resulted in muscle contraction paralleled by the presence of afferent spike potentials in the same and adjacent ventral roots. Others have noticed ventral root afferent potentials after peripheral nerve stimulation in the cat (Jankowska & Laporte, 1961) and afferent impulses from the distal end of cut ventral root filaments in the rat following strong skin stimulation (Dimsdale & Kemp, 1966). Renshaw (1946) hypothesized the presence of ventral root afferents in the rabbit and cat in order to explain the excitation of interneurons as a result of antidromic stimulation of the proximal stump of severed ventral roots. In addition, specific somatic sensory fibers have been identified in the ventral root of the cat by Kato and Hirata (1968). Impulses were recorded from the distal end of a cut ventral root after muscle stimulation, skin displacement and joint movement. Somatic afferent fibers were also found in cat ventral roots along with visceral afferents by Ryall and Piercy (1970). These authors demonstrated that the conduction velocity of ventral root afferents were similar to those of dorsal root fibers. And, it has recently been reported that 5 out of 129 proprioceptive and cutaneous afferents in cats projected their central processes into the ventral root (loeb, 1975). There is ample evidence, therefore, for the presence of afferent fibers in ventral roots.

An early report on the significance of ventral root afferents as a mediator of sensory information after dorsal rhizotomy for the relief of pain in man was made by Kidd in 1911. More recently, White and Sweet (1955) have reviewed many cases in which dorsal rhizotomy did not result in complete cessation of pain in man. However, these researchers commented on the need to examine for completeness of the dorsal rhizotomy, for segmental differences between nerves innervating skin and those innervating structures underlying the skin and for overlapping of receptive fields by adjacent nerve roots before looking for ventral root afferents. They also pointed to the fact that when an author referred to a ventral root as the mediator of the pain, it was not proven by sectioning that root in a subsequent surgical procedure. It was therefore concluded that "there is no positive evidence in man that pain of clinically significant degree enters the spinal cord over these roots" (p. 36). The authors also noted that many studies have shown that when the dorsal rhizotomy was extensive, and not confined to just a few roots, a complete absence of all sensation resulted in animals and in man. This finding was also stressed by Foerster (1913).

It is interesting to note that stimulation of the distal end of a cut ventral root in dogs was reported by Bernard (cited by White & Sweet, 1955) to cause "pain responses" when the dorsal root was preserved and that stimulation of the proximal end did not result in such responses. According to White and Sweet these findings probably reflected the presence of afferent sensory fibers which "may be taking a circuitous course to enter the cord by way of the posterior roots" (p. 32). This explanation seems sufficient to account for most of the electrophysiological data supporting ventral root afferents. However, Foerster and Gagel (1933) stimulated the proximal end of a cut ventral root in man and found that it caused pain in the same location as stimulation of the corresponding dorsal root. White and Sweet (1955) confirmed these findings in 6 out of 18 patients who had the proximal end of a cut ventral root stimulated. Furthermore, Maynard, Leonard, Coulter, Coggeshall, and Willis (1975) reported that ventral root afferents, representing central processes of dorsal ganglion cells, projected into the spinal cord in cats.

The origin and distribution of ventral root afferents has been discussed by several authors. Webber and Wemett (1966) sectioned the communicating rami near the sympathetic trunk in cats and found that half of the nerve cells observed in the ventral roots degenerated. This indicated to them that many of the processes from these nerve cells were distributed via the communicating rami and that many ventral root fibers might be visceral afferents. If so, they may travel along with autonomic nerves as large myelinated fibers from Pacinian corpuscles and as small myelinated and unmyelinated fibers from visceral receptors (Truex & Carpenter, 1969). It is noteworthy to mention that Ryall and Piercy (1970) found that ventral root afferents had similar conduction velocities to dorsal root fibers. This is electrophysiological evidence in favor of the presence of large myelinated afferents in the ventral root, similar to somatic or visceral sensory fibers.

Other neural structures have been sectioned or removed in order to isolate the origin of ventral root afferents. One example is removal of the dorsal root ganglion which does not result in loss of afferent impulses recorded from the distal end of a cut ventral root in the rat after cutaneous stimulation (Dimsdale & Kemp, 1966). More definitive work, however, done by Coggeshall et al. (1973, 1974) showed that dorsal root ganglionectomy was the only procedure that reduced the number of ventral root unmyelinated fibers in the cat while dorsal rhizotomy, peripheral nerve section and sympathectomy were ineffective. This indicated to the authors that most of the ventral root afferents arose from dorsal root ganglion cells. Since they were unmyelinated they were most probably small somatic and/or visceral afferents (Truex & Carpenter, 1969). Coggeshall et al. (1974) reported that there is evidence for myelinated ventral root afferents having skin or muscle receptive fields which suggest that some unmyelinated ventral root afferents may also have peripheral receptive fields.

BIBLIOGRAPHY

Adams, J. A. A closed-loop theory of motor learning. *Journal of Motor Behavior*, 1971, *3*, 111-149.

Adkins, R. J., Morse, R. W., & Towe, A. L. Control of somato-sensory input by cerebral cortex. *Science*, 1966, *153*, 1020-1022.

Allison, T., & Goff, W. R. Somatic evoked response recording: An adequate test of deafferentation? *Science*, 1973, *181*, 187-188.

Angel, R. W., Garland, H., & Fischler, M. Tracking errors amended without visual feedback. *Journal of Experimental Psychology,* 1971, *89*, 422-424.

Aschoff, J. C. Reconsideration of the oculomotor pathway. In F. O. Schmitt & F. G. Worden (Eds.), *The neurosciences: Third study program*. Cambridge, Mass.: The M I T Press, 1974.

Asratyan, E. A. The effect of use and disuse on morphology and function of spinal neurones. In E. Gutmann & P. Hnik (Eds.), *The effect of use and disuse on neuromuscular functions*. New York: Elsevier, 1963.

Beck, E. C., & Doty, R. W. Conditioned flexion reflexes acquired during combined catalepsy and de-efferentation. *Journal of Comparative and Physiological Psychology*, 1957, *50*, 211-216.

Berman, A. J. Deafferentation: Purposive movement in a unilaterally deafferented limb. *Electroencephalography and Clinical Neurophysiology*, 1970, *29*, 411. (Abstract)

Berman, A. J., & Berman, D. Fetal deafferentation: The ontogenesis of movement in the absence of peripheral sensory feedback. *Experimental Neurology*, 1973, *38*, 170-176.

Berman, A. J., & Taub, E. Purposive movement in a deafferented limb. *Transactions of the American Neurological Association*, 1966, *91*, 193-195.

Berman, A. J., Taub, E., Pomina, A. C., & Knapp, H. D. Further observations on deafferentation in the monkey. *Transactions of the American Neurological Association*, 1960, *85*, 198-199.

Berman, A. J., Teodoru, D., & Uyger, Z. Induced use of a unilaterally deafferented limb. *Experimental Neurology*, 1971, *32*(2), 176-183.

Berman, D., Derasmo, M., Marti, A., & Berman, A. J. Unilateral forelimb deafferentation in the monkey. Useful movement. *Advances in medical primatology*, 1978, in press.

Bizzi, E. The coordination of eye-head movements. *Scientific American*, 1974, *231*, 100-106.

Bossom, J. Time of recovery of voluntary movement following dorsal rhizotomy. *Brain Research*, 1972, *45*, 247-250.

Bossom, J. Movement without proprioception. *Brain Research*, 1974, *71*, 285-296.

Bossom, J., & Ommaya, A. K. Visuo-motor adaptation (to prismatic transformation of the retinal image) in monkeys with bilateral dorsal rhizotomy. *Brain*, 1968, *91*, 161-172.

Brooks, V. B. Information processing in the motorsensory cortez. In K. N. Leibovic (Ed.), *Information processing in the nervous system*. New York: Springer-Verlag, 1969, 231-243.

Brooks, V. B. Some examples of programmed limb movements. *Brain Research*, 1974, *71*, 299-308.

Brooks, V. B., Jasper, H. H., Patton, H. D., Purpura, D. P., & Brookhart, J. M. Symposium on cerebral and cerebellar motor control. *Brain Research*, 1970, *17*, 539-552.

Brown, T. G. The intrinsic factors in the act of progression in the mammal. *Proceedings of the Royal Society, London*, 1911, *84*, 308-319.

Burke, R. E. Control systems operating on spinal reflex mechanisms. *Neurosciences Research Program Bulletin*, 1971, *9*, 60-85.

Cannon, W. B. A law of denervation. *American Journal of the Medical Sciences*, 1939, *198*, 737-750.

Cannon, W. B., & Rosenblueth, A. *The supersensitivity of denervated structures: A law of denervation*. New York: MacMillan, 1949.

Cannon, W. B., & Haimovici, H. The sensitization of motoneurons by partial "denervation." _American Journal of Physiology_, 1939, _126_, 731-740.

Carpenter, M. B., Stein, B. M., & Shriver, J. E. Central projections of spinal dorsal roots in the monkey. II. Lower thoracic, lumbosacral and coccygeal dorsal roots. _American Journal of Anatomy_, 1968, _123_, 75-118.

Chambers, W. W., Liu, C. N., & McCouch, G. P. Anatomical and physiological correlates of plasticity in the central nervous system. _Brain, Behavior and Evolution_, 1973, _8_, 5-26.

Chang, H-T. Activation of internuncial neurons through collaterals of pyramidal fibers at cortical level. _Journal of Neurophysiology_, 1955, _18_, 452-471.

Chow, K. L., Mathers, L. H., & Spear, P. D. Spreading of uncrossed retinal projection in superior colliculus of neonatally enucleated rabbits. _Journal of Comparative Neurology_, 1973, _151_, 307-322.

Clare, M. H., Landau, W. M., & Bishop, G. H. Electrophysiological evidence of a collateral pathway from the pyramidal tract to the thalamus in the cat. _Experimental Neurology_, 1964, _9_, 262-267.

Coggeshall, R. E., Coulter, J. D., & Willis, W. D., Jr. Unmyelinated fibers in the ventral root. _Brain Research_, 1973, _57_, 229-233.

Coggeshall, R. E., Coulter, J. D., & Willis, W. D., Jr. Unmyelinated axons in the ventral roots of the cat lumbosacral enlargement. _Journal of Comparative Neurology_, 1974, _153_, 39-58.

Cohn, R., Jakniunas, A., & Taub, E. Summated cortical evoked response testing in the deafferented primate. _Science_, 1972, _178_, 1113-1115.

Cooper, S., & Daniel, P. M. Muscle spindles in human extrinsic eye muscles. _Brain_, 1949, _72_, 1-24.

Cooper, S., Daniel, P. M., & Whitteridge, D. Afferent impulses in the oculomotor nerve, from the extrinsic eye muscles. _Journal of Physiology_, 1951, _113_, 463-474.

Crawford, W. A. _The perception of moving objects. VII. Some observations on the presence of proprioceptive information from extraocular eye muscles._ London: Flying Personnel Research Committee, Air Ministry, 1960. (Memo 150F)

DeLong, M. Central patterning of movement. Neurosciences Research Program Bulletin, 1971, 9, 27-30.

Denny-Brown, D. The cerebral control of movement. Springfield, Illinois: Charles C. Thomas, 1966.

Deutsch, J. A., & Deutsch, A. Physiological Psychology. Homewood, Illinois: Dorsey Press, 1966.

Dimsdale, J. A., & Kemp, J. M. Afferent fibers in ventral nerve roots in the rat. Journal of Physiology, 1966, 187, 25P-26P.

Drake, C. G., & Stavraky, G. W. An extension of the "Law of Denervation" to afferent neurones. Journal of Neurophysiology, 1948, 11, 229-239.

Eccles, J. C., Eccles, R. M., & Shealy, C. N. An investigation into the effect of degenerating primary afferent fibers on the monosynaptic innervation of motoneurons. Journal of Neurophysiology, 1962, 25, 544-558.

Eccles, J. C., Fatt, P., & Koketsu, K. Cholinergic and inhibitory synapses in a pathway from motoraxon collaterals to motoneurones. Journal of Physiology, 1954, 126, 524-562.

Eccles, R. M., & Lundberg, A. Supraspinal control of interneurones mediating spinal reflexes. Journal of Physiology, 1959, 147, 565-584.

Edds, M. V., Jr. Collateral nerve regeneration. Quarterly Review of Biology, 1953, 28, 260-276.

Engberg, I., & Lundberg, A. An electromyographic analysis of muscular activity in the hindlimb of the cat during unrestrained locomotion. Acta Physiologica Scandinavica, 1969, 75, 614-630.

Evarts, E. V. Activity of ventralis lateralis prior to movement in the monkey. Physiologist, 1970, 13, 191. (Abstract)

Evarts, E. V. Feedback and corollary discharge: A merging of the concepts. Neurosciences Research Program Bulletin, 1971, 9, 86-112.

Festinger, L., & Canon, L. K. Information about spatial location based on knowledge about efference. Psychological Review, 1965, 72, 373-384.

Foerster, O. On the indications and results of the excision of the posterior spinal nerve roots in men. Surgery, Gynecology and Obstetrics, 1913, 16, 463-474.

Foerster, O. Symptomatologie der krankungen des ruckenmarks und seiner wurzelin. In B. Foerster, *Handbook of Neurology*, 1936, *5*, 1-403. (Chang, H. T., & Ruch, T. C. Organization of the dorsal columns of the spinal cord and their nuclei in the spider monkey. *Journal of Anatomy*, 1947, *81*, 140-149.)

Foerster, O., & Gagel, O. Uber afferente nervenfasern in den vorderen wurzeln. *Z. ges Neurol, Psychiat.*, 1933, *144*, 313-324. (White, J. C., & Sweet, W. H. *Pain: Its mechanisms and neurosurgical control*. Springfield, Ill.: Charles C. Thomas, 1955.)

Freeman, L. W. Functional recovery in spinal rats. In W. F. Windle (Ed.), *Regeneration in the central nervous system*. Springfield, Ill.: Charles C. Thomas, 1955.

Gelfan, S. Neurone and synapse populations in the spinal cord: Indication of role in total integration. *Nature*, 1963, *198*, 162-163.

Gianutsos, J. G. *Feedback contributions to recovery in the deafferented primate forelimb*. Unpublished doctoral dissertation, Adelphi University, 1975.

Gianutsos, J. G., & Berman, A. J. Role of vision in recovery of function following forelimb deafferentation in the monkey. *Neuroscience Abstracts*, 1975, *1*, 519.

Goldberger, M. E. Personal communication, Oct. 29, 1975.

Goldberger, M. E., & Murray, M. Restitution of function and collateral sprouting in the cat spinal cord: The deafferented animal. *Journal of Comparative Neurology*, 1974, *158*, 37-54.

Gooddy, W. Sensation and volition. *Brain*, 1949, *72*, 312-339.

Goodman, D. C., & Horel, J. A. Sprouting of optic tract projections in the brain stem of the rat. *Journal of Comparative Neurology*, 1966, *127*, 71-88.

Granit, R., Pascoe, J. E., & Steg, G. The behaviour of tonic and motoneurones during stimulation of recurrent collaterals. *Journal of Physiology*, 1957, *138*, 381-400.

Guzman-Flores, C., Buendia, N. & Lindsley, D. B. Cortical and reticular influences upon evoked responses in dorsal column nuclei. *Federation Proceedings*, 1961, *20*(1), 330. (Abstract)

Guzman-Flores, C., Gault, F. P., Anderson, C., & Lindsley, D. B. Pyramidal influences upon potentials evoked in sensory nuclei. Boletin del Instituto de Estudios Medicos y Biologicos, 1963, 21, 65-75.

Hein, A. Recovering spatial motor coordination after visual cortex lesions. In D. A. Hamburg, K. H. Pribram & A. J. Stunkard (Eds.), Perception and its disorders. Baltimore: Williams & Wilkins, 1970.

Hein, A., & Held, R. A neural model for labile sensorimotor coordinations. In E. E. Bernard & M. R. Kare (Eds.), Biological prototypes and synthetic systems, Vol. 1). New York: Plenum Press, 1962.

Hein, A., Held, R., & Gower, E. C. Development and segmentation of visually controlled movement by selective exposure during rearing. Journal of Comparative and Physiological Psychology, 1970, 73, 181-187.

Hering, H. E. Ueber centripetale ataxie beim Menschen und beim Affen. Neurol. Zbl., 1897, 16, 1077-1094. (Bossom, J. Movement without proprioception. Brain Research, 1974, 71, 285-296.)

Holst, E. von. Relations between the central nervous system and the peripheral organs. British Journal of Animal Behaviour, 1954, 2, 89-94

Holst, E. von., & Mittelstaedt, H. The reafference principle. In R. Martin (Ed. and trans.), The behavioural physiology of animals and man: The collected papers of Erich von Holst I. Coral Gables, Florida: University of Miami Press, 1973. (Reprinted from Naturwissenschaften, 1950, 37.)

Hultborn, H., Jankowska, E., & Lindstrom, S. Recurrent inhibition from motor axon collaterals in interneurones monosynaptically activated from la afferents. Brain Research, 1968, 9, 367-369.

Jankowska, E. & Laporte Y. Recherche de fibres afférentes dans les racines ventrales lombo-sacrées chez le chat. Comptes Rendus des Séances de la Société de Biologie, Paris, 1961, 155, 1582-1585.

Jones, B. Facilitation of visual perception through voluntary movement in elementary school children. Journal of Experimental Child Psychology, 1972, 14, 408-415. (a)

Jones, B. Outflow and inflow in movement duplication. Perception and Psychophysics, 1972, 12, 95-96. (b)

Jones, B. Is there any proprioceptive feedback? Comments on Schmidt (1971). Psychological Bulletin, 1973, 79, No. 6, 386-388.

Jones, B. The importance of memory traces of motor efferent discharges for learning skilled movements. Developmental Medicine and Child Neurology, 1974, 16, 620-628. (a)

Jones, B. Role of central monitoring of efference in short-term memory for movements. Journal of Experimental Psychology, 1974, 102, 37-43. (b)

Kato, M., & Hirato, Y. Sensory neurons in the spinal ventral roots of the cat. Brain Research, 1968, 7, 479-482.

Kidd, L. J. Afferent fibres in ventral spinal roots. British Medical Journal, 1911, 2, 359-360.

Kirk, E. J., & Denny-Brown, D. Functional variation in dermatomes in the Macaque monkey following dorsal root lesions. Journal of Comparative Neurology, 1970, 139, 307-320.

Knapp, H. D., Taub, E., & Berman, A. J. Effect of deafferentation on a conditioned avoidance response. Science, 1958, 128, 842-843.

Knapp, H. D., Taub, E., & Berman, A. J. Conditioned response following deafferentation in the monkey. Transactions American Neurological Association, 1959, 185-187.

Knapp, H. D., Taub. E. & Berman, A. J. Movements in monkeys with deafferented forelimbs. Experimental Neurology, 1963, 7, 305-315.

Konorski, J. Changing concepts concerning physiological mechanisms of animal motor behaviour. Brain, 1961, 84, 277-294.

Lassek, A. M. Inactivation of voluntary motor function following rhizotomy. Journal of Neuropathology and Experimental Neurology, 1953, 12, 83-87. (a)

Lassek, A. M. Potency of isolated brachial dorsal roots in controlling muscular physiology. Neurology, 1953, 3, 53-57. (b)

Lassek, A. M. Motor deficits produced by posterior rhizotomy versus section of the dorsal funiculus. Neurology, 1954, 4, 120-123.

Lassek, A. M. Effect of combined afferent lesions on motor function. Neurology, 1955, 5, 269-272.

Lassek, A. M. & Moyer, E. K. An ontogenetic study of motor deficits following dorsal brachial rhizotomy. Journal of Neurophysiology, 1953, 16, 247-251.

Laszlo, J. I. Training of fast tapping with reduction of kinaesthetic tactile, visual and auditory sensations. Quarterly Journal of Experimental Psychology, 1966, 19, 344-349.

Laszlo, J. I. Kinaesthetic and exteroceptive information in the performance of motor skills. Physiology and Behavior, 1967, 2, 359-365.

Laszlo, J. I., & Bairstow, P. J. The compression block technique: A note on procedure. Journal of Motor Behavior, 1971, 3, 313-317.

Laszlo, J. I., & Baker, J. E. The role of visual cues in movement control and motor memory. Journal of Motor Behavior, 1972, 4, 71-77.

Levitt, M., Carreras, M., Liu, C. N., & Chambers, W. W. Pyramidal and extrapyramidal modulation of somatosensory activity in gracile and cuneate nuclei. Archives Italiennes de Biologie, 1964, 102, 197-229.

Lewis, M. McD., & Porter, R. Pyramidal tract discharge in relation to movement performance in monkeys with partial anaesthesia of the moving hand. Brain Research, 1974, 71, 345-351.

Lewis, M. McD., Porter, R., & Horne, M. The effects of impairment of afferent feedback from the moving limb on the natural activities of neurones in the precentral gyrus of conscious monkeys: A preliminary investigation. Brain Research, 1971, 32, 467-473.

Li, C-L. Activity of interneurons in the motor cortex. In H. H. Jasper, L. D. Proctor, R. S. Knighton, W. C. Norsbay, & R. T. Costello (Eds.), Reticular formation of the brain. Boston: Little, Brown, 1958.

Liu, C. N., & Chambers, W. W. Intraspinal sprouting of dorsal root axons. A.M.A. Archives of Neurology and Psychiatry, 1958, 79, 46-61.

Liu, C. N., & Chambers, W. W. A study of cerebellar dyskinesia in the bilaterally deafferented forelimbs of the monkey (Macaca mulatta and Macaca speciosa). Acta Neurobiologiae Experimentalis, 1971, 31, 263-289.

Lloyd, D. P. C. Centripetal discharges in dorsal and ventral roots following stimulation of muscle by ventral root volleys. Society for Experimental Biology and Medicine, Proceedings, 1941, 47, 44-47.

Loeb, G. E. Ventral root projections of myelinated dorsal root ganglion cells in the cat. Neuroscience Abstracts, 1975, 1, 142.

Loeser, J. D., & Ward, A. A. Some effects of deafferentation on neurons of the cat spinal cord. Archives of Neurology, 1967, 17, 629-636.

Ludvigh, E. Possible role of proprioception in the extra-ocular muscles. Archives of Ophthalmology (American Medical Association), 1952, 48, 436-441

Lund, R. D., & Lund, J. S. Synaptic adjustment after deafferentation of the superior colliculus of the rat. Science, 1971, 171, 804-807.

Lynch, G., Deadwyler, S., & Cotman, C. Postlesion axonal growth produces permanent functional connections. Science, 1973, 180, 1364-1366.

MacKay, D. M. Cerebral organization and the conscious control of action. In J. C. Eccles (Ed.), Brain and conscious experience. New York: Springer-Verlag, 1966.

Magnus, R. Korperstellung. Berlin: Julius Springer, 1924. (Corbin, K. B. & Hinsey, J. C. Intramedullary course of the dorsal root fibers of each of the first four cervical nerves. Journal of Comparative Neurology, 1935, 63, 119-126.)

Matin, L., Matin, E., & Pearce, D. G. Visual perception of direction when voluntary saccades occur. 1. Relation of visual direction of a fixation target extinguished before a saccade to a flash presented during the saccade. Perception & Psychophysics, 1969, 5, 65-80.

Maynard C. W., Leonard, R. B., Coulter, J. D., Coggeshall, R. E., & Willis, W. D. Cells of origin of ventral root afferents. Neuroscience Abstracts. 1975, 1, 141.

McCouch, G. P. Comments on regeneration of functional connections. In W. F. Windle (Ed.), Regeneration in the central nervous system. Springfield, Ill.: Charles C. Thomas, 1955.

McCouch, G. P., Austin, G. M., Liu, C. N., & Liu, C. Y. Sprouting as a cause of spasticity. Journal of Neurophysiology, 1958, 21, 205-216.

Merton, P. A. The accuracy of directing the eyes and the hand in the dark. Journal of Physiology, 1961, 156, 555-577.

Merton, P. A. Absence of conscious position sense in the human eyes. In M. B. Bender (Ed.), The oculomotor system. New York: Harper & Row, 1964. (a)

Merton, P. A. Human position sense and sense of effort. In G. M. Hughes (Ed.), Homeostasis and feedback mechanisms. The 18th Symposium of Society for Experimental Biology. London: Cambridge University Press, 1964. (b)

Mikeladze, A. L. On terminations of afferent nerve fibres in lumbo-sacral region of spinal cord. Arkhiv Anatomii Gistologii I Embriologii, Leningrad, 1965, 48, 3-12. (Abstract)

Millar, J., Basbaum, A., & Wall, P. Restructuring of the somatotopic map and appearance of abnormal neuronal activity in the gracile nucleus after partial deafferentation. Experimental Neurology, 1976, 50, 658-672.

Mott, F. W., & Sherrington, C. S. Experiments upon the influence of sensory nerves upon movement and nutrition of the limbs. Proceedings of the Royal Society of London, 1895, 57, 481-488.

Munk, H. Ueber die Functionon von Hirn und Ruckenmark. Berlin: Hirschwald, 1909. (Knapp, H. D., Taub, E., & Berman, A. J. Movement in monkeys with deafferented forelimbs. Experimental Neurology, 1963, 7, 305-315.)

Murray, M., & Goldberger, M. E. Restitution of function and collateral sprouting in the cat spinal cord: The partially hemisected animal. Journal of Comparative Neurology, 1974, 158, 19-36

Nathan, P. W., & Sears, T. A. Effects of posterior root section on the activity of some muscles in man. Journal of Neurology, Neurosurgery & Psychiatry, 1960, 23, 10-22.

O'Donnell, J., & Windle, W. An experimental study of the sensory neurones in the ventral spinal nerve roots of the cat. Anatomical Record, 1932, 55, 117-126.

Paillard, J., & Brouchon, M. A proprioceptive contribution to the spatial encoding of position cues for ballistic movements. Brain Research, 1974, 71, 273-284.

Ramon y Cajal, S. [Degeneration and regeneration of the nervous system] (R. M. May, Ed. and trans.). London: Oxford University Press, 1928. (Liu, C. N., & Chambers, W. W. Intraspinal sprouting of dorsal root axons. A. M. A. Archives of Neurology and Psychiatry, 1958, 79, 46.)

Renshaw, B. Influence of discharge of motoneurons upon excitation of neighboring motoneurons. Journal of Neurophysiology, 1941, 4, 167-183.

Renshaw, B. Central effects of centripetal impulses in axons of spinal ventral roots. Journal of Neurophysiology, 1946, 9, 191-204.

Ryall, R. W., & Piercy, M. F. Visceral afferent and efferent fibers in sacral ventral roots in cats. Brain Research, 1970, 23, 57-65.

Schmidt, R. A. A schema theory of discrete motor skill learning. Psychological Review, 1975, 82, 225-260.

Sharpless, S. K. Reorganization of function in the nervous system - use and disuse. Annual Review of Physiology, 1964, 26, 357-388.

Sherrington, C. S. On the anatomical constitution of nerves of skeletal muscles; with remarks on recurrent fibres in the ventral spinal nerve-root. Journal of Physiology, 1894, 17, 211-258.

Sherrington, C. S. The integrative action of the nervous system. New Haven: Yale University Press, 1906. (a)

Sherrington, C. S. Observations on the scratch-reflex in the spinal dog. Journal of Physiology, 1906, 34, 1-50. (b)

Sherrington, C. S. Quantitative management of contraction in lowest level co-ordination. Brain, 1931, 54, 1-28.

Sherrington, C. S., & Laslett, E. E. Observations on some spinal reflexes and the interconnection of spinal segments. Journal of Physiology, 1903, 29, 58-96.

Shriver, J. E., Stein, B. M., & Carpenter, M. B. Central projections of spinal dorsal roots in the monkey. I. Cervical and upper thoracic dorsal roots. Journal of Anatomy, 1968, 123, 27-74.

Skavenski, A. A., Haddad, G., & Steinman, R. M. The extraretinal signal for the visual perception of direction. Perception & Psychophysics, 1972, 11, 287-290.

Sperry, R. W. Neural basis of the spontaneous optokinetic response produced by visual inversion. Journal of Comparative and Physiological Psychology, 1950, 43, 482-489.

Steinbach, M. J., & Held, R. Eye tracking of observer-generated target movements. Science, 1968, 161, 187-188.

Taub, E. Prism compensation as a learning phenomenon: A phylogenetic perspective. In S. J. Freedman (Ed.), The neuropsychology of spatially oriented behavior, Homewood, Ill.: Dorsey Press, 1968.

Taub, E., Bacon, R. C., & Berman, A. J. Acquisition of a trace-conditioned avoidance response after deafferentation of the responding limb. Journal of Comparative and Physiological Psychology, 1965, 59(2), 275-279.

Taub, E., Barro, G., Parker, B., & Gorska, T. Utility of a limb following unilateral deafferentation in monkeys. Society for Neuroscience, Abstract, 1972, 213.

Taub, E., & Berman, A. J. Avoidance conditioning in the absence of relevant proprioceptive and exteroceptive feedback. Journal of Comparative and Physiological Psychology, 1963, 56(6), 1012-1016.

Taub, E., & Berman, A. J. The effect of massive somatic deafferentation on behavior and wakefulness in monkeys. Paper presented at Psychonomic Society Meeting, Niagra, Ontario, October, 1964.

Taub, E., & Berman, A. J. Movement and learning in the absence of sensory feedback. In S. J. Freedman (Ed.), The neuropsychology of spatially oriented behavior. Homewood, Ill.: Dorsey Press, 1968.

Taub, E., Ellman, S. J., & Berman, A. J. Conditioned grasp response in a deafferented primate limb. American Psychologist, 1964, 19, 510. (Abstract)

Taub, E., Ellman, S. J., & Berman, A. J. Deafferentation in monkeys: Effect on conditioned grasp response. Science, 1966, 151, 593-594.

Taub, E., Goldberg, I. A., Bossom, J., & Berman, A. J. Deafferentation in monkeys: Adaptation to prismatic displacement of vision. Paper read at Eastern Psychological Association, New York, April 1966.

Taub, E., Goldberg, I., & Taub, P. Deafferentation in monkeys: Pointing at a target without visual feedback. Experimental Neurology, 1975, 46, 178-186.

Taub, E., Perrella, P. N., Barro, G. Behavioral development in monkeys following bilateral forelimb deafferentation on the first day of life. Transactions American Neurological Association, 1972, 97, 101-104. (a)

Taub, E., Perella, P. N., & Barro, G. Motor capacity following somatosensory deafferentation on first day of life in monkeys. Federation Proceedings, 1972, 31, 821. (b)

Taub, E., Perrella, P. N., & Barro, G. Motor effects of combined forelimb deafferentation and eyelid closure on day of birth in monkeys. Psychonomic Science, 1972, 29, 327. (c) (Abstract)

Taub, E., Perrella, P., & Barro, G. Behavioral development after forelimb deafferentation on day of birth in monkeys with and without blinding. Science, 1973, 181, 959-960.

Taub, E., Schlossberg, S., Teodoru, D., & Barro, G. Compensation for loading of an unseen limb in deafferented monkeys. Unpublished manuscript, Institute for Behavioral Research, Silver Springs, Maryland, 1975.

Taub, E., Teodoru, D., Ellman, S. J., Bloom, R. F., & Berman, A. J. Deafferentation in monkeys: Extinction of avoidance responses, discrimination and discrimination reversal. Psychonomic Science, 1966, 4, 323-324.

Teasdall, R. D., & Stavraky, G. W. Responses of deafferented spinal neurons to corticospinal impulses. Journal of Neurophysiology, 1953, 16, 367-375.

Teuber, H-L. Perception. In J. Field, H. W. Magoun, & V. E. Hall (Eds.), Handbook of physiology: Neurophysiology III. Washington, D. C.: American Physiological Society, 1960.

Teuber, H-L. Speech as a motor skill with special reference to non-aphasic disorders. Society for Research in Child Development Monographs, 1964, 29, 134-135.

Truex, R. C., & Carpenter, M. B. Human Neuroanatomy (6th ed.). Baltimore: Williams & Wilkins, 1969.

Twitchell, T. E. Sensory factors in purposive movement. Journal of Neurophysiology, 1954, 17, 239-252.

Vaughan, H. Jr., Gross, E. G., & Bossom, J. Cortical motor potential in monkeys before and after upper limb deafferentation. Experimental Neurology, 1970, 26, 253-262.

Walker, A. E., & Weaver, T. J., Jr. The topical organization and termination of the fibers of the posterior columns in Macaca mulatta. Journal of Comparative Neurology, 1942, 76(1), 145-156.

Webber, R. H., & Wemett, A. Distribution of fibers from nerve cell bodies in ventral roots of spinal nerves. Acta Anatomica, 1966, 65, 579-583.

Werner, G. Neural information processing. In F. O. Schmitt & F. G. Worden (Eds.), *The neurosciences: Third study program*. Cambridge, Mass.: The M I T Press, 1974.

White, J. C., & Sweet, W. H. *Pain: Its mechanisms and neurosurgical control*. Springfield, Ill.: Charles C. Thomas, 1955.

Wilson, V. J. Regulation and function of Renshaw cell discharge. In R. Granit (Ed.), *Muscular afferents and motor control, Nobel Symposium I*. New York: John Wiley & Sons, 1966.

Windle, W. F. Neurons of the sensory type in the ventral roots of man and of other mammals. *Archives of Neurology and Psychiatry*, 1931, *26*, 791-800.

Windle, W. F. Comments on regeneration in the human central nervous system. In W. F. Windle (Ed.), *Regeneration in the central nervous system*. Springfield, Ill.: Charles C. Thomas, 1955.