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AN OPERANT APPROACH TO REHABILITATION MEDICINE: OVERCOMING LEARNED NONUSE BY SHAPING

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A new approach to the rehabilitation of movement, based primarily on the principles of operant conditioning, was derived from research with deafferented monkeys. The analysis suggests that a certain proportion of excess motor disability after certain types of injury involves a learned suppression of movement and may be termed learned nonuse. Learned nonuse can be overcome by changing the contingencies of reinforcement so that they strongly favor use of an affected upper extremity in the chronic postinjury situation. The techniques employed here involved 2 weeks of restricting movement of the opposite (unaffected) extremity and training of the affected limb. Initial work with humans has been with chronic stroke patients for whom the approach has yielded large improvements in motor ability and functional independence. We report here preliminary data suggesting that shaping with verbal feedback further enhances the motor recovery.

Key words: shaping, training, restriction, somatosensory deafferentation, stroke, rehabilitation medicine, impaired movement, monkeys, humans

This article describes a new approach to the rehabilitation of movement in physical medicine. It is based in its essential features on the principles of operant conditioning. It is fitting that it appear in a tribute to Joseph V. Brady, because he persuasively endorsed the relevance and importance of applying the principles of the experimental analysis of behavior to new areas and in this way strongly influenced the development of this work.

Experiments with Deafferented Monkeys

Although the present approach is fundamentally behavioral, the original observations were made in the context of studies of the neurophysiology of motor control and the role of sensory feedback in movement and learning. The spinal nerves, which are fundamental for these functions, emerge from the spinal cord in two roots. The dorsal root is sensory. Thus,

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It is appropriate that this article appear in a tribute to Joseph V. Brady, because the basic approach that it represents stems from research carried out with monkeys given somatosensory deafferentation in a laboratory of the Institute for Behavioral Research (IBR) in Silver Spring, Maryland. Joe Brady was first a member of the Board of Directors of IBR and then Chairman of the Board. The animal rights group, People for the Ethical Treatment of Animals (PETA), tried to gain custodianship of the colony of deafferented monkeys; if they had succeeded, it would have set a dangerous legal precedent that would have had serious adverse effects on the future ability to conduct animal research in the United States. As Chairman of the IBR Board of Directors and, thus, the main representative of the owner of the monkeys, Joe Brady was subjected to an enormous amount of pressure to release the monkeys to PETA or agents that it designated. Some, but not all, of this pressure consisted of a petition demanding this action signed by a majority of the members of Congress, attempts at persuasion by direct contact by more than one half dozen members of Congress, attempts by NIH to convince him to accede to the political pressure, and the very negative reaction of his own university to his involvement in the situation. Nevertheless, Joe Brady, recognizing the importance of the case for the future integrity of the animal-research enterprise, responded by saying, to quote him, "They will get those monkeys over my dead body." As a result, the monkeys were preserved so that significant experiments could be carried out (Pons et al., 1991; Rausell, Cusick, Taub, & Jones, 1992). These experiments will not be described here because their subject matter is not directly relevant to the main theme of this paper, but there is widespread recognition of their potential practical importance for the fields of cortical plasticity and physical rehabilitation (Barinaga, 1992; Palca, 1991; Stephens, 1991). Thus, Joe Brady resisted pressure that very few could have withstood, and thereby achieved a significant victory for animal research on several levels. However, his role in this incident is largely unknown. He is an unsung hero. It is hoped that this account will help to some extent to begin to rectify this situation.

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produce movement. The early postsurgical spinal shock also may be partly due to active inhibitory processes. As time elapses following deafferentation, recovery processes, which are at present incompletely understood, raise the background level of excitability of motoneurons so that movements can once again, *at least potentially*, be expressed. The period of spinal shock lasts from 2 to 6 months in monkeys following forelimb deafferentation (Taub, 1977; Taub & Berman, 1968).

Several converging lines of evidence suggest that nonuse of a single deafferented limb is a learning phenomenon involving a conditioned suppression of movement (Taub, 1977, 1980). The restraint and training techniques appeared to be effective because they altered the contingencies of reinforcement, thereby enabling the learned nonuse to be successfully overcome. Thus, immediately after operation, the monkeys cannot use a deafferented limb; recovery from spinal shock requires considerable time. An animal with one deafferented limb tries to use that extremity in the immediate postoperative situation, but it cannot. Continued attempts to use the deafferented limb often lead to painful and otherwise aversive consequences such as incoordination and falling, as well as to loss of food objects, and, in general, to failure of any activity attempted with the deafferented limb. The resultant punishment leads to a conditioned suppression of attempts to use the limb. Moreover, the animal gets along quite well in the laboratory environment on three limbs; thus, these patterns of behavior are therefore positively reinforced and as a result are strengthened. The tendency not to use the deafferented extremity persists, and consequently the monkeys never learn that, several months after operation, the limb has become potentially useful.

When the movements of the intact limb are restricted several months after unilateral deafferentation, the contingencies of reinforcement are changed dramatically. The animal either uses the deafferented limb or it cannot with any degree of efficiency feed itself, move about, or carry out a large portion of its normal activities of daily life. This change in the contingencies of reinforcement "overcomes" the learned nonuse of the deafferented limb and induces the animal to use it. However, if the movement-restricting device is removed a short time after the early display of operant movement, the newly learned use of the deafferented limb acquires little strength and is, therefore, quickly overwhelmed by the well-learned tendency not to use the limb. If the movement-restriction device is left on for several days or longer, however, use of the deafferented limb acquires strength and is then able to compete successfully with the learned nonuse of that limb in the free situation. The learned nonuse formulation has received direct experimental support from two studies (Taub, 1977, 1980).

Shaping had several advantages over the conditioned-response training employed in our earlier work that enabled generalization of new use of the deafferented limb to the free situation: (a) There was the obvious advantage of a slow, step-wise procedure that could gradually lead an organism from a rudimentary initial response level to more complex responses. By allowing the extent of progress to determine the amount of time spent at each step, behavioral requirements did not exceed behavioral capacity excessively; thus, the likelihood of failure was reduced. (b) The responses being shaped more closely resembled those carried out in daily life in complexity and functional significance than did the type of simple and artificial movements adopted for convenience in the conditioning situations. (c) The shaping series took place over a much longer period of time and involved much more training than was the case in the conditioned-response situations.

Shaping stands partway between our earlier conditioned-response training and restricting movement of the intact limb, both conceptually and empirically, in its ability to enable generalization from the experimental intervention to the natural environment. Although shaping and intact-limb restriction represent two different approaches to the rehabilitation of movement, they are not mutually exclusive; indeed, from the outset they appeared to be potentially complementary. These two procedures were not employed jointly in the research with monkeys; however, it seemed reasonable to attempt this approach in the work with human stroke patients described below.

The mechanism of learned nonuse is depicted schematically in Figure 1, and the method by which techniques that overcome learned nonuse operate is presented in Figure 2. These models explain the motor phenomena that follow forelimb deafferentation in mon-

OVERCOMING LEARNED NONUSE

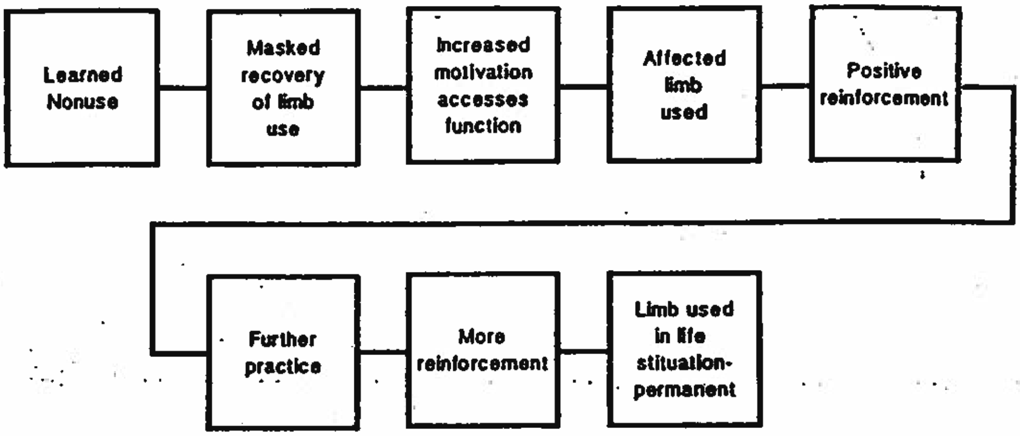

Fig. 2. Schematic model of mechanism for overcoming learned nonuse.

will not exhibit any further improvement for the rest of their lives. The focal criterion for inclusion in the study was the ability to extend at least 20° at the wrist and 10° at the fingers.

Nine persons who met the study's inclusion criteria (Taub et al., 1993) were assigned by a random process to either an experimental group (4 subjects) or to an attention-comparison group (5 subjects). The subjects in the two groups were closely matched in initial motor ability and did not diverge significantly in major demographic characteristics or in chronicity (median 4.1 years for the restraint group; median 4.5 years for the comparison group).

For the experimental group, the unaffected limb was secured in a resting hand splint and was then placed in a sling; the affected arm was left free. The restraint was to be worn at all times during waking hours except when specific activities were being carried out (e.g., excretory functions, naps, and situations in which balance might be compromised). A behavioral contract was drawn up for each subject, and in each case he or she agreed to spend approximately 90% of waking hours in restraint. The restraint devices were worn for 12 days. On each of the 8 weekdays during this period, patients spent 7 hr at the rehabilitation center and were given a variety of tasks to be carried out by the paretic upper extremity for 6 hr (e.g., eating lunch with a fork and spoon; throwing a ball; playing dominoes, Chinese checkers, or card games; writing on paper or on a chalk board; pushing a broom; using the Purdue Dexterity Board; taking the Minnesota Rate of Manipulation Test). No explicit training of any kind, including shaping, was given; the subjects simply practiced the tasks repeatedly. The purpose was primarily to provide experience and overtraining in use of the affected limb.

The procedures given to the comparison group were designed to focus attention on the involved extremity. This was accomplished in three ways. First, patients were told (during four periods on separate days) that they had much greater motor ability with their affected extremity than they were exhibiting; they were exhorted to focus attention at home on using the affected extremity in as many new activities as possible. Examples were given, and record keeping was required and monitored. Second, patients received two sessions (labeled physical therapy) that involved only those activities that required neither active movement nor limbering of the involved limb. Third, patients were given self-range-of-movement exercises to carry out at home for 15 min a day. In these exercises, the affected extremity was passively moved into a variety of positions by the unaffected extremity.

Two laboratory tests of motor function were

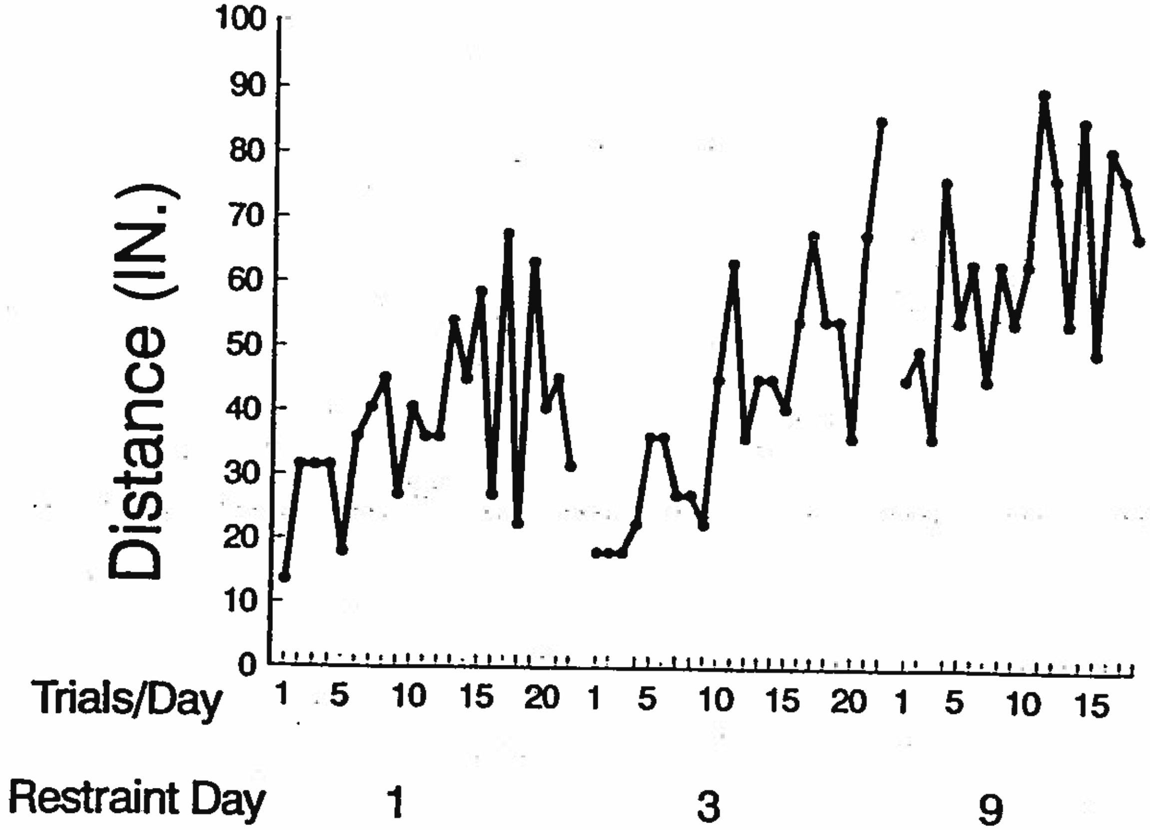

Fig. 3. Shuffleboard task. Distance disk moved over trials. Data are from three consecutive shaping sessions in which an attempt was made to increase the distance that a shuffleboard disk could be cast by a pole held by the affected upper extremity of a chronic stroke patient. Sessions occurred on Days 1, 3, and 9 of restraint of the unaffected limb.

described here are those for which data are provided in Figures 3 through 5. Other tasks are listed below to provide the reader with a general idea of the nature of the training program.

Shuffleboard. This task involved casting a shuffleboard disk with a pole as far as possible along a court from a standard starting position and a standard standing posture. The parameters shaped were (a) distance from start line to the leading edge of the disk and (b) the quality of movement rated on a 5-point scale employed in a previous study with stroke patients (Taub et al., 1993, in which the criteria for each step are explicitly defined). This task tended to be favored by subjects, presumably because of its recreational associations and because it provided direct and immediate feedback as to performance relative to previous attempts. The main joints involved were shoulder and elbow. The left edge of the court was demarcated at 22.9-cm intervals with distance-labeled horizontal strips of red plastic tape to give subjects immediate information about the distance of each cast. The leading edge of the disk on the farthest cast of a current session and the farthest cast of each previous session for that subject were indicated by strips of red tape placed in the middle of the lane, thus providing a continuous indication of the nature of the present behavioral requirement.

Rotation of Rolodex® file. A Rolodex® file (12.7 cm diameter) had to be rotated by a seated subject by turning one of two knobs (5.7 cm diameter) protruding from the center of either side of the file. The movement required was grasp (of the knob) and ulnar deviation and some flexion of the wrist. The arm of the subject was unsupported and had to be kept in flexion at shoulder and elbow. All joints of

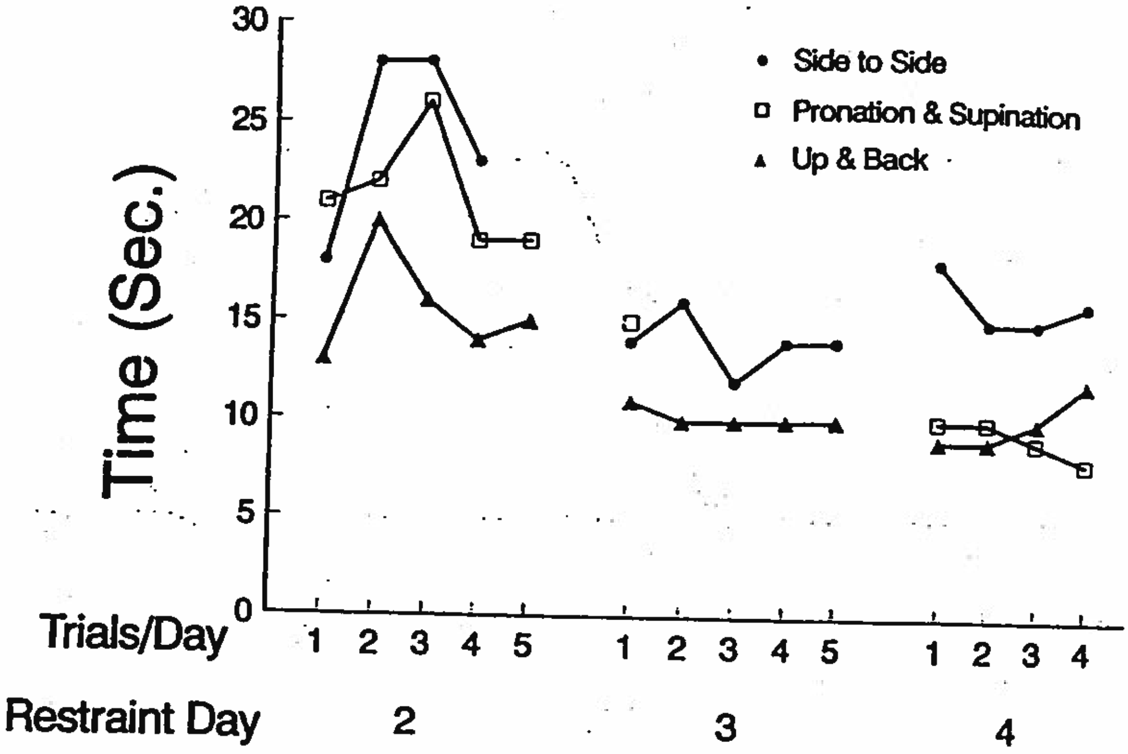

Fig. 5. Rolling ball task. Data are from consecutive shaping sessions for three subtasks involving movement of an 8-in. (20.3-cm) diameter ball on a table in front of the seated subject: (1) sliding ball from side to side, (2) rotating ball by supinating and internally rotating arm, and (3) sliding ball toward and away from the torso. The *y* axis displays the time(s) to perform eight side-to-side movements, four pronation/supination movements, or four backward/forward movements.

Additional tasks included tap telegraph key, place ring on a prong in front of the subject, place ring on a prong above the subject, trace circles, shave (simulated), pat powder puff on face, brush teeth (simulated), dot-to-dot drawing, use children's building blocks to create a tower, place graduated weights on different height boxes, write signature, and use spoon or fork with simulated pieces of food.

General considerations. All training is carried out with movement of the unimpaired upper extremity restricted by a resting hand splint and sling. At the beginning of work with a subject, new tasks are often designed that are tailored to provide training for the movements that are weakest in that individual. Each task must have aspects that are easily quantifiable, preferably so that small improvements are immediately apparent to the subject. Rest intervals are introduced in each shaping session. The rest periods are usually the same length as the trial periods, though longer intervals are sometimes used to prevent fatigue. Verbal reinforcement is given enthusiastically after the smallest performance improvements are detectable. The experimenter's verbal response is intended to provide detailed information in terms of the specific nature of the improvement. In addition, maintenance of previous gains is acknowledged on each occasion. Performance regressions are never punished and are usually ignored. When performance has not increased for approximately three trials, the subject is encouraged to improve further (e.g., "Let's see whether we can go a little further on the next try"). Liberal use is made of modeling and prompts. At the beginning of a shaping series, subjects may be given physical help in carrying out parts of a movement sequence they cannot do themselves. In physical therapy, this is termed "assisted movement." This aid is attenuated and then faded as soon as is feasible. If a subject is having too much trouble making progress in a task, a simpler date of this writing), the score remained at virtually the same level of improvement (3.7). Paired t tests revealed that the improvement from baseline values was statistically significant from the 5th day of treatment until the 8th week of follow-up (ps from .006 to .0001). A parallel rating form completed by the subject's wife confirmed that improvement in functional ability had occurred. Her ratings increased, although not quite as much as her spouse's, from 2.1 (slight use) at pretreatment to 3.1 (moderate use) 1 week after the end of treatment.

At the time of this writing, 2 additional chronic stroke patients have just completed treatment for overcoming learned nonuse under shaping protocols. The data have not yet been analyzed, but inspection indicates that the results for these subjects are somewhat better than for the 1st subject. For the 2nd subject, for example, mean MAL score went from 0.8 pretreatment to 3.0 posttreatment, and for the 3rd subject, mean MAL score increased from 0.3 (0 = no use) to 3.1 for the same period. These ratings were confirmed by the independent scores of significant others on collateral forms. The 1st subject was not given a posttreatment home practice program and, as noted, his MAL score did not improve substantially during follow-up. In contrast, the second 2 subjects were given home practice programs and reported using them. The 2nd subject improved from 3.0 at the end of treatment to 3.9 and 3.4 at the 1st and 2nd weeks of follow-up, respectively. The 3rd subject's scores increased from 3.1 at the end of treatment to 4.3 (4.0 = almost normal) at the end of the 3rd follow-up week when he reported driving a car using both hands to steer and sharing cooking duties with his wife.

The new data reported here are from the first 3 subjects given shaping as part of the effort to overcome learned nonuse. These preliminary results are promising, and suggest that behavioral shaping improves the therapeutic outcome. However, data from additional subjects given similar treatment are needed before conclusions can be drawn concerning the quantitative role of shaping in the recovery of motor function.

During the 2nd week of shaping, the 2nd subject repeated with wonder several times a day some variant of the following quote, "I guess I stopped trying to use my left [affected] arm. I just didn't realize it." On an experiential level, this is an excellent encapsulation of the phenomenon of learned nonuse. We have had similar reactions from most of our previous subjects.

General Summary

Supervised practice of the use of an impaired upper extremity (but not shaping), in combination with restriction of an unimpaired limb, greatly increased the motor improvement that occurred in stroke patients compared to the improvement observed when only the motor restriction portion of the overcoming-learned-nonuse protocol was employed (Wolf et al., 1989). The data reported here from 3 subjects suggest that by substituting shaping for uninstructed task practice, motor improvement can be improved still further. Because shaping is simply a technique for improving the efficiency of certain types of training, it is conceptually reasonable that this should be the case. However, the data are at present limited, and firm conclusions are therefore not yet warranted.

The analysis given earlier in this article suggests that the development of learned nonuse is based upon the operation of the contingencies of reinforcement that are in effect following an injury that produces an initial motor deficit. It follows that the development of learned nonuse should not be confined only to cases of somatosensory deafferentation in monkeys and stroke in humans, but should occur in some proportion of individuals after many different types of injury. The operation of this mechanism would be disabling if there was a subsequent slow recovery or healing whose potential motor effects were masked by the learned nonuse. As noted above, the mechanism is behavioral and, as such, should be relatively independent of the locus of the injury. Therefore, it is proposed that learned nonuse is a factor in the development of some excess motor disability. (For a more complete discussion see Taub, 1994.) This is a widespread clinical phenomenon that occurs in connection with a number of conditions (Taub, 1980), especially in the aged; it is characterized by a motor deficit that is greater than appears to be warranted by the organic status of the individual.

Strokes almost always involve unilateral upper extremity motor deficits. Restricting the movement of the unimpaired upper extremity

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