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ABSTRACT

The project described here focused on obtaining basic information on the memory representation of movement stimuli. When a learner makes a simple movement and is later asked to reproduce it, what is abstracted from the first movement that allows accurate reproduction of the second. The underlying assumption of the project was that unless basic knowledge about how movement information is represented, stored and retrieved, practical considerations on how to teach motor skills will be ill-founded. Thus this report describes a series of experiments which were directed toward that goal in an attempt to isolate the contributions of movement information. Findings that examine the relative contributions of central and peripheral components in simple movement control are summarized, and educational implications are presented. (Author/RD)

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"Assimilation and Developmental Processes of a Perceptual Trace in Kinesthetic Memory and a Model of Kinesthesis"

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ABSTRACT

The project described here focused on obtaining basic information on the memory representation of movement stimuli. When a learner makes a simple movement and is later asked to reproduce it, what is abstracted from the first movement that allows accurate reproduction of the second? The underlying assumption of the project was that unless basic knowledge about how movement information is represented, stored and retrieved, practical considerations on how to teach motor skills will be ill-founded. Thus the report describes a series of experiments directed toward that goal. Systematically, experiments are reported that attempt to isolate the contributions of movement information. The report summarizes the findings that examine the relative contributions of central and peripheral components in simple movement control. The subsequent section (appendix) gives the actual experiments that were performed in their published form.

Introduction

The study of motor behavior deals primarily with how the human learns and controls his movements in the environment. Despite great interest in this important aspect of human behavior, little is actually known about the acquisition and retention of movement patterns and skills. With increased leisure time becoming more apparent in the United States, one of the educational goals of many physical education programs across the country is to teach the average student fundamental movement patterns as well as specific sport skills. Equipped with these skills, students would be able to participate in life-long leisure activities which provide a good balance with their professional careers. Without scientific research, knowledge about the learning process may be difficult to obtain and can only hinder the accomplishment of these educational objectives.

A contributing element to the lack of knowledge of the motor learning process has been the preoccupation with applied research. This type of motor skill research has been concerned with answering specific problems such as how to kick a ball, how to drive a car and how to operate a machine. Even with this concern for obtaining useful knowledge of learning and performance in many tasks, applied research has yielded disconnected pockets of information which have lacked general scientific principles (Adams, 1971). To fully understand the acquisition process of <u>all</u> motor skills, it is desirable to work from a theoretical framework which tries to uncover the general principles of motor learning.

Fortunately, some recent theories of motor learning (Adams, 1971; Schmidt, 1975) have been postulated which contain a conceptual framework and provide testable predictions. These theoretical formulations as well as others in experimental psychology have evolved from behaviorism or S-R psychology which had dominated experimental psychology for more than a century. Rather than viewing the learner as a passive recipient of environmental stimuli, these information processing or cognitive theories view the learner as an active decision maker and organizer of his own actions. Also, these theories assume that a number of central processes exist within the learner that transform environmental stimuli into useful information which is used to base his thoughts and actions upon.

The acquisition of motor skills is in many respects dependent on the retention of past movements since it is quite clear that more accurate responses are unlikely if the memory of previous movements fails. Thus, at the heart of information processing accounts of motor learning are variables which influence the retention of movement. Many of these variables have been localized at peripheral origins such as visual and proprioceptive feedback and are dependent on the results of movement. Rather recently, other variables influencing movement retention have been shown to be of more central origins and are apparently dependent on the learner's active organization of his movements. The approach taken in this project over the past four years has been to study the relative contribution of peripheral and central components of motor skill. This report reviews and sumarizes the experiments, conducted in my laboratory over the last four years, that have application to the memory representation of movement.

Peripheral and Central Components of Movement Retention

The learning process can be epitomized as a constant interaction between the learner and the environment. Many decisions faced by the learner must be based upon the interpretation of environmental stimuli through the visual, auditory and proprioceptive modalities. Thus, feedback from the environment as well as from the learner's actual movements is thought to play an important role in the acquisition and retention process. The contribution of feedback, a peripheral component of movement, has been extensively studied in my laboratory. Along with investigations which have studied behavioral techniques designed to manipulate feedback, a number of experiments are reported which have examined the relative contribution of proprioceptive, visual and auditory feedback in the retention of movement. Proprioceptive feedback has been shown to subserve many movement cues such as position, amplitude, speed and acceleration. These various types of movement information could potentially be stored in memory and be one basis for movement retention. Several experiments have been conducted in the project specifically investigating location (position) and distance (amplitude) cues and these are reported.

A number of experiments have been performed concerning the influence of one movement on the production of another. Most of the available evidence points to a peripheral mechanism of this so-called "response biasing" effect. These studies which have composed a substantial part of my research program are reported.

Until quite recently, the central components of skill acquisition and retention have been largely ignored. One central component of the movement retention process is the manner in which the learner actively rehearses or maintains movement information in memory. Another central process which has been shown to be a determiner of movement retention is the active organization and implementation of voluntary movements. Both of these central components have received considerable experimentation in this project.

The Research Questions. Perhaps the major contemporary issue in motor-behavior research concerns the development of a central or internal-memory representation which is postulated as necessary for guiding and controlling movement. Whether it is hypothesized as a perceptual trace (Adams, 1971), a schema (Pew, 1974; Schmidt, 1975), a neural model (Sokolov, 1969), a spatial reference or coordinate system (Lashley, 1951; Paillard & Brouchon, 1968), a standard (Laszlo & Bairstow, 1971), or a template (Keele, 1968; Keele & Summers, 1976) there seems to be universal agreement that some such agent is critical for governing movement. The fundamental concern for which sources of information are actually used in developing a memory representation for movement is the focus of this project.

Clearly, there are a variety of information sources which can contribute to the development of a memory representation (e.g., vision and audition). On the other hand, there are many situations in which the learner must depend on cues arising as the results of his own movements, per se. Such cues are thought to be based on proprioception, the encompassing term for the modality subserving sense of position and movement. In addition, it has been hypothesized that the central nervous system also has mechanisms available by which it can inform itself as to the intended output (Merton, 1970). Thus movement information can be considered as "peripheral," in the sense that it arises from proprioceptive receptor organs stimulated as a result of movement; or "central," in the sense that internal information is generated prior to the occurrence of overt movement.

The relative roles of peripheral and central information in movement coding have ~~yet to be assessed in any systematic manner. Therefore, the~~ primary questions addressed in this project focus on the receptor and effector mechanisms involved when a subject produces a motor response and is later asked to duplicate it. What information does the subject rely on in this situation? What does he encode? And what is the nature of the storage code on which reproduction is based?

A. Peripheral Components

The coordination of human motor performance is no doubt dependent on the interplay between the peripheral and central mechanisms of the body. Peripheral components are assumed to be localized at the various sensory receptors which transmit movement information. With limb movement, it is well known that kinesthetic feedback cues can arise from a variety of sources, joint position receptors, muscle spindles, and cutaneous senses. Additionally, feedback can come from a variety of sources associated with the movement via certain modalities. Often, auditory and visual cues accompany a movement along with proprioceptive information. Many models and theories of motor performance have delegated important role feedback. Essentially these closed-loop theories assume that ongoing feedback is compared against some internal reference of the correct movement and any discrepancies are treated as errors to be corrected (Adams, 1971; Anokhin, 1969; Bernstein, 1967; Schmidt, 1975; Sokolov, 1969).

1. Feedback and motor control. The importance of proprioceptive information can generally be assessed by either reducing or increasing its presence during the performance of a motor task. Its importance is inferred if either a reduction of its presence hinders performance or a heightening of its presence is facilitory. While motor control has been demonstrated to be independent of proprioceptive feedback in certain insects (Wilson, 1961), amphibia (Szekely, Czech & Voros, 1969) and mammals (Taub, Perrella, & Barro, 1973), the findings for man are less conclusive (Lashley, 1917). A principal drawback to the investigation of such phenomena in the latter has been an inability to eliminate information from the kinesthetic modality. Since surgical deafferentation, being the common technique utilized in studies of motor control on lower phyla, is not

experimentally possible in human subjects, a variety of methods using temporary nerve blocks has been adopted (Merton, 1964; Provins, 1958). Common criticisms of the latter have been directed first, to the question of whether such techniques eliminate all movement feedback, and second, to whether they are sufficiently selective to only impede tactile and kinesthetic afferent processes, without incurring similar and conjunctive detrimental effects on motor systems.

Quite recently, assumptions have been made regarding "the nerve compression block technique"[1] which deny both of the above criticisms. Implicit to the use of this technique is the fundamental postulate that function in nerve fibers and receptors subserving kinesthesis is eliminated 5-10 min. prior to that in those subserving motor function, thus allowing a time interval in which an experimental task can be investigated prior to the onset of motor impairment (Laszlo & Bairstow, 1971a). On the basis of this assumption, decrements in performance found under nerve block conditions have been attributed solely to the reduction of kinesthetic feedback (Docherty, 1973, Laszlo, 1967a), although Keele (1968), in his review, has alluded to the possibility that some of the decrement found in Laszlo's (1966, 1967b) work may also have been due to efferent damage.

Such a conclusion might indeed be overdrawn in light of electrophysiological evidence which indicates that nerve fibers responsible for kinesthetic information transmission and motor function have very similar micron diameters (Boyd & Davy, 1968) and conduction velocities (Buchthal & Rosenflack, 1965). Furthermore, relevant research indicates that neural transmission in sensory and motor fibers is similarly affected by ischemia induced by pneumatic cuff (Fullerton, 1963; Seneviratne & Peiris, 1968).

Thus, there appears to be little physiological support for a functional dissociation between sensory and motor fibers in the manner claimed by proponents of the nerve compression-block technique. It seems possible, therefore, that decrements in motor performance found under block conditions could be due to a combination of impairment in both neural mechanisms.

While such questions have traditionally proved difficult to answer, it is proposed that an analysis of nerve fibers can be determined. In particular, motor nerve conduction parameters presents one method by which the functional status of the nerve fibers can be determined. In particular, motor nerve conduction velocity (NCV) and the amplitude of the evoked action potential under nerve block conditions would appear to be of significance to the issue of motor impairment. Reduction in motor NCV is known to cause dispersion of impulses as they reach the muscle resulting in a less synchronized activation and consequently less summation of the individual muscle fiber action potentials. Such denervation limits the usefulness of the muscles (Hodes, Larragee, & German, 1948). Similarly, since amplitude serves as an index of the number of muscle fibers concerned in contraction (Harvey & Masland, 1941), a reduction in the number of innervated muscle fibers would cause a decrease in amplitude, and consequent decrements in motor function.

Findings such as these, should they occur prior to or in conjunction with kinesthetic information loss, would present serious methodological problems for the nerve compression block as utilized by Laszlo (1966). Furthermore, since the function of the motor program in the movement control model proposed by Laszlo and Bairstow (1971b) is to select the appropriate motor units in correct spatio-temporal sequence (Keele, 1968, 1973), and since the motor units depend on normal neural impulse transmission for proper functioning (Marinacci, 1968), no drastic decrements in motor nerve conduction should be observed under block conditions until 5-10 min. after kinesthetic feedback has been effectively eliminated.

Thus two studies performed in this project were designed to examine the viability of the nerve compression block procedure in assessing motor performance after kinesthetic feedback elimination. In the first experiment (Kelso, Stelmach & Wanamaker, 1974; see Appendix) by monitoring nerve conduction (namely, conduction velocity and amplitude of the muscle action potential) in the ulnar and median nerves of the upper preferred limb under compression block conditions, we found progressive decrements in neural transmission as the block progressed. Little neural function remained at the time that kinesthetic "cut off" was assigned (24.9 min). Contrasting with several of Laszlo's studies (Laszlo, 1967; Laszlo, Shamoon and Sanson-Fisher, 1969) most subjects were unable to perform a simple tapping task at that point, even after repeated block applications. We concluded from this experiment that the technique confounded kinesthetic loss and motor impairment.

Since the apparent discrepancy between Laszlo's and our performance data could hinge around the assignment of kinesthetic "cut off," it seemed important to us to monitor motor performance in conjunction with sensory discrimination without assigning tactile and kinesthetic endpoints. Therefore, in the second experiment (Kelso, Wallace, Stelmach & Weitz, 1975; see Appendix) performance on a tapping task was assessed in relation to sensory discrimination throughout the duration of the block. On the assumptions of the nerve compression block technique, efficient motor performance should be possible when subjects can no longer discriminate tactile and kinesthetic stimuli. The findings indicated however that significant decrements in tapping measures occurred somewhat earlier in the time course of the block than decreases in kinesthetic discrimination. Also, contrary to assumption, the majority of subjects ceased to perform prior to total kinesthetic loss. The data suggested that motor impairment is a crucial issue in the use of this technique, and provided further behavioral support for the neurological findings of the previous study.

Educational Implications. In recent years the nerve "compression block technique" has been utilized extensively as a means of investigating motor control in the absence of kinesthesis. With this method the conclusions drawn have questioned the importance of kinesthesis in motor skill acquisition. These findings, if proven to be correct, would have far reaching implications for the teaching of motor skills. Not only would less attention have to be focused on kinesthetic cues, but greater emphasis would have to be placed on selecting and developing motor programs or internal models. This view contrasts sharply with the views of teachers of motor skills who are currently directing the learner's attention to kinesthetic cues and emphasizing kinesthetic awareness.

The results of the experiments performed seriously challenged the finding of the previous research. It was shown that previous investigators failed to consider the motor impairment issue when using the nerve block technique. Thus these experiments have tempered the view that motor skills acquisition is not dependent on kinesthetic feedback.

In the two previous studies, performance on a relatively well learned tapping task was examined. Motor skill research is also concerned with the acquisition and retention of new movements. Proper experimental control often demands certain limitations with regards to the type of responses to be examined and it is safe to say that the more complex the movement the more difficult it is to be examined in an experimental setting. Thus much of the work in my laboratory has investigated the acquisition and retention of very simple movements e.g. lever or linear positioning.

2. Feedback and short-term retention of movements. The concern of the two previous studies was to determine whether proprioceptive feedback aids or enhances motor control. Another question of interest is whether feedback contributes to the memory representation of movement. I have argued elsewhere that to make an accurate reproduction requires a memory trace about a past movement and immediate ongoing feedback from the responding limb. Presumably, the subject moves until the ongoing feedback matches a memory trace held in storage. The strength of a given trace is thought to be a function of the amount of feedback and the exposure to it (Adams, 1971). Previous studies have demonstrated that there is memory loss over short periods of time with unfilled retention intervals. Most likely this forgetting is due to a rapidly decaying memory trace (Adams & Dijkstra 1966; Posner, 1967; Stelmach, 1969; Williams et al. 1969). Recently Adams, Marshall & Goetz, (1972), using various combinations of feedback, have demonstrated that forgetting is related to the amount and type of feedback available. With absolute error, forgetting was small under augmented and great under minimal feedback conditions. Augmented feedback was interpreted to produce a stronger trace, thereby allowing the subject to make better discriminations at reproduction. Since only one learn-reproduction trial was used and there was considerable forgetting with reduced feedback, a trace decay interpretation was supported.

It is generally thought that feedback plays a major role in all motor learning, thus the generality of this foregoing finding on a linear positioning task should be predicted for other motor tasks. Yet, it has been demonstrated in the past that generalizing from one task to another is often tenuous. For this reason, I examined whether augmented kinesthetic feedback on a lever task aids reproduction compared to a minimal feedback condition (Stelmach, 1973; see Appendix). A second question was: if a memory trace is strengthened, does it decay at a slower rate than a non-augmented one? The task involved the reproduction of movement which was initially presented under heightened or minimal feedback conditions. The augmented feedback condition consisted of the presentation and reproduction of a movement with visual, auditory and heightened proprioceptive cues. This was accomplished by the experimenter opening a shutter, so that the subject could see his movement, engaging a clicker, allowing the subject to hear his movement and by applying increased tension, thereby providing heightened proprioceptual cues to the subject. Minimal feedback conditions consisted of no visual and auditory cues and minimal proprioceptive cues (absence of tension).

Augmented feedback was found to markedly reduce errors at reproduction accuracy. Apparently the additional feedback provided a stronger trace and at reproduction it was easier for the subject to match the ongoing feedback than that of the trace in storage. As such, feedback appears to be an important variable in studying short-term movement retention. This result agrees with the findings of Adams et al. (1972). Using a linear positioning task, they also found increased feedback markedly reduced reproduction error. In addition, the data support Adams' (1971) notion that a perceptual trace is imprinted with feedback from all modalities and its strength is determined by the amount of feedback available.

Yet, the difficulty with this study was that it could not deliniate the relative contribution of the three modalities being manipulated. The superior reproduction of the augmented feedback condition over the minimal condition could have been due to heightened visual, auditory, or proprioceptive cues or perhaps some combination thereof. An experiment was performed (Stelmach & Kelso, 1975; see Appendix), using a slightly different paradigm, in order to determine the potency of each modality in the establishment of an internal representation of movement. Five different feedback conditions were used. In the minimal feedback condition; which served as a control group, the subject received no visual, auditory or heightened proprioceptive information. In a visual condition, the subject could see his hand and arm be displaced at the lever during the criterion presentation and reproduction. Similarly, in the auditory condition, the subject was able to hear his lever movements. Heightened proprioceptive cues were provided in another condition while in the last group, subjects received feedback information via the manipulation of all these modalities. The basic finding was that the group which had heightened feedback from all modalities and the group which had only heightened visual feedback were not significantly different from each other but both were superior to the remaining conditions. Adams' (1971) closed-loop theory asserts that the strength of a given movement trace is dependent on the amount of practice and feedback impinging upon it. Adams, Goetz, & Marshall (1972) and I (Stelmach, 1973) have provided evidence to support this notion; both investigations finding that augmented feedback provided markedly reduced reproduction errors in comparison to a condition where the subject had minimal proprioceptive information. With regard to this experiment, the data suggested that vision may be more important in strengthening the criterion trace, since kinesthetic and auditory cues by themselves did not seem to affect reproduction to any great degree. This finding agrees with Adams and Goetz (1973) who found that visual cues were dominant in regulating the perceptual trace, and raises the question of whether a change is needed in Adams' (1971) original construct that all feedback channels are equally involved in the control of movement.

Educational Implications. One of the primary concerns of teachers of motor skills is what type of movement cues should be emphasized during learning to improve retention. For most motor tasks, there are three main catagories of movement information that can be augmented. These are visual, kinesthetic and auditory cues. The two previous experiments attempted in a laboratory situation to examine which of these cues would minimize retention loss of simple movements over short delay periods. This information would be useful for teachers because they would be in a position to know which are the best cues to stress during the acquisition processes.

From the results it is clearly suggested that the emphasis should be on combining the visual, kinesthetic and auditory when possible. However, in situations where only one cue can be augmented, the findings suggest that visual information produces the biggest effect on reducing retention loss.

3. Movement Codes. Proprioception is an all encompassing term which represents afferent movement information of the conscious and subconscious type. Visual and auditory information generally escapes this categorization although it is quite clear that many movements have visual and auditory consequences. Receptors which are thought to contribute to movement perception include organs in the joints, labyrinths, ligaments, muscles and tendons. Touch and pressure receptors are also thought to signal some movement information. The receptors which have been the locus of much neurophysiological research are those in the joints and muscles. While there is much controversy regarding muscle receptor contribution to conscious perception of movement (Goodwin, McCloskly & Mathers, 1972; Granit, 1970) there is little doubt among scientists that joint receptors perform this function.

Thus proprioceptive information can be referred to as the conscious sensation of movement mainly derived from joint receptors. If people are dependent on joint information for movement sensation, an important question to ask is what information can the joint receptors potentially generate?

Numerous neurophysiological studies have undergone attempts to answer this question. Skoglund (1956) is generally credited with identifying three types of receptors found in the joints and surrounding tissue. Two of these receptor types, the Ruffini-like endings found in the joint capsule and the Golgi endings found in the ligaments of the joint, were slow adapting receptors. Vater-Pacini corpuscles, found also in the joint capsule, were rapid adapting receptors. The work of Skoglund and others (Boyd, 1954; Boyd & Roberts, 1953; Burgess & Clark, 1969) indicates that the fast adapting receptors fire only when the joint is moved and are dependent on direction and velocity. Furthermore, slow adapting receptors emit rather steady discharges when the joint is stationary and thus are dependent on the held position. Another point of interest is that Burgess and Clark (1969), Lynn (1975) and Skoglund (1956) indicate that joint receptor activity increases greatly when the limb approaches maximum extension or flexion. Activity at the intermediate angles is less.

In summary, there is neurophysiological evidence that velocity, direction, and position information may be transmitted from joint receptors. But physiological evidence is not sufficient for the central storage of joint receptor information (Russell, 1974). In fact, whether this information reaches higher centers responsible for conscious perception does not insure that this information can be stored and maintained in memory. Rather than identifying the specific neuronal structures and pathways in the central nervous system, behavioral studies attempt to uncover the processes responsible for storage and maintenance of information in memory. Generally, the information processing technique is one in which certain variables are chosen which are assumed to affect certain central processes (Massaro, 1975). If changes in performance accompany the manipulations of the variables, then the nature of the processes can be more clearly defined. For example, in verbal memory the storage of information has been shown to be dependent on the stimulus attributes available. (Murdock, 1974). Likewise, the retention of movements has been shown to be dependent on the type of proprioceptive information available for storage and maintenance processes.

As far back as the late nineteenth and early twentieth centuries it was realized that many potential proprioceptive cues can arise from a simple limb movement (e.g. Hollingworth, 1909; Woodworth, 1899). For example, both Hollingworth and Woodworth felt that distance or extent information was an important cue for reproduction. Woodworth's belief that distance information was a unique dimension for movement coding can be captured in a quotation from his dissertation. "There must be a sense of the extent (distance) of movement, a sense which is not reducible to a sense either of its force or of its duration or of its initial and terminal position (p. 80)." Unfortunately, Woodworth did not supply us with much data to back up his claim. Another difficulty with Woodworth's assertion is that there are no known distance receptors which can directly transmit extent information to the higher centers. It is possible, however, that distance information can be derived somehow from velocity signals. Similarly, a subtraction between the beginning and end positions of a movement could conceivably give a person a sense of the distance moved. These derivations would seemingly be based on velocity or position information contrary to Woodworth's notion.

The point is, however, that Woodworth was certainly aware of the possibility that many kinds of cues could be potentially stored into memory. With the exception of a few others during that era (Hollingworth, 1909; Leuba, 1909) the multi-cue idea lay dormant for nearly sixty years.

It is suggested from neurophysiological work (e.g., Skoglund, 1956) that velocity, direction and position cues are subserved by joint receptors. Research in the last ten years however, has been mainly preoccupied with distance (extent) and location (position) cues. In order to isolate distance and location cues the following technique has been adopted (e.g., Laabs, 1973; Marteniuk & Ryan, 1972). After completing the criterion movement, the lever of a linear positioning apparatus is repositioned to a different starting position by the experimenter. If the subject is asked to reproduce only the end location of the criterion movement, a different distance must be traveled to reach it. Thus in this condition distance information is not readily available to the subject. The subject needs only to store and remember the criterion movement endpoint. However, if the subject accurately reproduces the actual distance travelled on the criterion movement, he will necessarily go beyond the criterion movement endpoint (if the starting position is forward). Likewise, the subject will fall short of the criterion movement endpoint if the new starting position is backward. Under these latter two conditions, the subject needs to store and remember the distance of the criterion movement.

One of the first studies conducted in this part of the project was concerned with the effect of changes in starting positions on the reproduction of distance and location information (Stelmach & Kelso, 1973; Stelmach & McCracken, 1976; see Appendix). Of main interest was whether the relative changes in direction and amplitude of starting positions systematically altered error in reproduction when distance or location was the primary cue. The findings indicated that when the location cue was primary, the comparison of starting combinations did not produce any significant differences. The procedure of altering combinations of starting positions should have reduced the subject's information from timing, speed of movement, and motor outflow sources. This finding appears to support the view that the subject can disregard distance cues when the reproduction of a terminal location is required.

While the evidence was not overwhelming, the reproduction of a distance appears to be somewhat more susceptible to alterations in combinations of starting position than location. These results can be taken as evidence that the subject has difficulty in using only distance cues. From these data, it appears that both distance and location cues are affected to some degree by combinations of starting position, although location appears somewhat more stable than distance. The resistance of location, and susceptibility of distance cues to alterations in starting positions might indicate that information about location is encoded at a higher level than information about distance. However, when viewed from these findings, the superior codability of location over distance appears to be a matter of degree.

Further evidence that location reproduction is superior to distance was gathered in another experiment performed under the grant. (Stelmach, Kelso & Wallace, 1975, Exp. 1; see Appendix). Blindfolded subjects in this experiment were allowed to plan and produce a response of their choice on a linear positioning apparatus. After a 15 second retention interval, subjects were asked to reproduce either end location or the distance of the criterion movement from a new starting position. The results showed that location reproduction was superior to distance reproduction except for short movements (0-23 cm) where the reverse was true. Thus these results are generally in agreement with those of other investigations (Laabs, 1973; Marteniuk, 1973, Marteniuk & Roy, 1972; Marteniuk, Shields & Campbell, 1972; Moxley, 1974).

In summary, it has been shown that location information is generally better reproduced than distance information. This suggests that locational aspects of movement are a more important dimension for movement coding and it is highly unlikely that location cues can be derived from distance information. For example, Marteniuk and Roy (1972) induced random limb movements prior to the arrival of the location to be reproduced. If subjects were using distance information to derive the final end position, reproduction should be quite poor because the actual movement path was highly disorganized. The results indicated that reproduction in this condition was identical to a condition where random movements were not imposed on the subject. This finding suggests that what is needed by the subject to reproduce location is information regarding the specific endpoint. The question is, what kind of information? It has been shown that there are rather direct neuronal linkages between joint receptors and the sensori-motor cortex (Mountcastle et al. 1963). It may be that the proprioceptive location information transmitted by these linkages is stored during the criterion movement and later recovered during the reproduction movement. This would suggest that location reproduction is greatly dependent on specific proprioceptive information which was generated from the criterion movement.

Educational Implications. The basic problem for motor skill research is to uncover the sources of information used by the learner during acquisition. While there are many information sources that surround performance that are available to the learner, the most important is perhaps the information from the movements themselves. When a learner makes a movement and is asked to reproduce it, what did the learner abstract from the original movement that allowed him/her to make an accurate reproduction? To examine this question, behavioral scientists have forced the learner to be dependent on two different movement characteristics that subserve kinesthesis: movement endpoint information, dynamic movement informants (amplitude) or both. At issue is which of these sources of information can contribute to better retention. To put it another way, what should the learner attend to during the movement to facilitate retention? Results obtained have shown that movement endpoint information is a very dominant aspect of movement retention. While these findings stress the importance of location cues, they have also implicated a role for movement amplitude information as they can also be shown to contribute to retention accuracy. These findings have deepened our understanding of how we learn and control movements.

The target hypothesis was originally developed by MacNeilage (1970) to overcome a perplexing problem in speech production. The basic problem which bewildered MacNeilage was how the human could position the articulators to a required location specific to a given phoneme from virtually any starting position. For example, how is it that we can position our articulators (lips, jaws, tongue) to utter the phoneme "p" regardless of when this phoneme is to be produced (e.g., pin, spin, slip)? As Russell (1974) notes "ignoring the rate-related differences, the problem of sequentially accessing in memory the correct set of commands to produce a required utterance seems enormous" (p. 5). Although the target hypothesis does not explain the learning of articulatory positions for phoneme locations, it does suggest that phoneme locations are represented in memory as points within a three-dimensional coordinate system. The production of a given phoneme involves the cognition of what to produce as well as the spontaneous generation of a movement to a given location within the coordinate criterion movement. The assumption was that the subject should receive more accurate location information, the longer he remains on the designated position. This assumption was based on previous findings which indicated the potency of location duration on location reproduction (Wallace & Stelmach, 1975; see Appendix) It was felt that if the subject was using location information from the starting and finishing points of the criterion movement in order to derive distance information that location duration manipulations should effect distance reproduction. The results were disappointing in that no strong location duration effects were found in any of the experiments. The failure to demonstrate the potency of this variable in distance reproduction does not necessarily reject the notion that location cues aid distance reproduction. It may be that just a few milliseconds of exposure is sufficient to encode location information in a distance reproduction task and our minimal exposure conditions were from 300-400 msec in duration. At the present time, two experiments are being conducted which further examine the possibility that location information contributes to distance reproduction.

4. Response biasing. Skilled activity usually involves the coordination of numerous movement patterns in the proper spatial-temporal order. It is therefore quite common for a given movement to be preceded or followed by another. Difficulties may occur in accurately retaining a movement in memory due to the influence of interpolated movements. Some interpolated movements that deviate from a criterion response have been shown to produce sizable directional shifts in the constant errors at reproduction. If an interpolated movement is of a greater extent or intensity than the criterion, reproduction error is influenced in the positive direction. Similarly, if an interpolated movement is of lesser

extent or intensity, constant error reproduction is shifted in a negative manner. This response biasing effect has received considerable experimentation during the project and the following discussion summarizes this work and related work from other investigators.

Directional response biasing has been found in several studies using positioning tasks. Craft & Hinricks (1971) examined this phenomenon by systematically varying the similarity of interfering movements executed prior to or after the criterion response. The length of the interfering movement produced significant shifts in constant error with response biasing being inversely related to the similarity of interfering movements to the criterion. An experiment performed in my laboratory (Stelmach & Walsh, 1972; see Appendix) using a lever positioning task showed that a single interpolated movement was a potent variable in producing response biasing. The interpolated movements were 35° or 45° beyond the criterion targets or 35° or 45° less than the targets. This experiment demonstrated that the longer the subject remained at the interpolated location (5 or 20 sec) the greater the response biasing. These results were interpreted to indicate that the increased biasing over time was due to the criterion memory trace decaying and becoming more susceptible to interference from an interpolated memory trace. Thus, the relative decay state between the two memory traces was viewed as determining the amount of response biasing.

In a subsequent experiment to examine the foregoing interpretation, Stelmach & Walsh (1973, see Appendix) held constant the duration and location aspects of the interpolated movements within the retention interval. The relative state interpretation would predict that as the temporal proximity of the interpolated movement to reproduction increases, response biasing should increase in magnitude. The results showed that positive response biasing was associated with the longer movements, and temporal order effects were found for the two longest retention intervals. When the prebiasing interval was held constant (postbiasing left to vary), the positive error shift tapered off over time, suggesting that when the interpolated trace is allowed to decay, the amount of biasing decreases.

Temporal order effects like those just reported have also been reported by Herman and Bailey (1970) and Patrick (1971). In both of these studies, the shorter the interval between the interpolated movement and the criterion, the more response biasing was found. In the latter study, one delayed interpolated response produced as much biasing as five repeated movements of the same extent. These recent findings lend support to an interpretation that can account for the relative decay states of the criterion and interpolated memory traces.

In a further test of the relative decay state hypothesis, Stelmach & Kelso (1975; see Appendix) attempted to strengthen either the criterion or the interpolated response to examine if memory trace strength was a factor in the magnitude of the response biasing. Augmented feedback in the form of added visual and auditory cues and heightened kinesthetic cues were used to manipulate trace strength. The relative state hypothesis would predict that response biasing would be decreased or increased depending on the strength of the criterion or interpolated memory traces. The weaker the criterion trace at the time of the interpolated act, the greater the interference effect should be. Memory trace strength as manipulated produced considerable change in the constant errors and markedly reduced variable errors.

Response biasing has been found to be influenced by the magnitude of the interpolated response, by the time spent at a deviant location, and by the temporal occurrence of an interpolated movement. These findings taken together seem to indicate a peripheral mechanism.

Evidence for a central mechanism is suggested by Trumbo et al. (1972) who found that increased response biasing was associated with preselected and voluntarily stopped movements as opposed to experimenter-stopped or constrained movements. Clearly, if preselected movements result in superior reproduction, it may be postulated that they possess a stronger representation in memory. As such they may provide a means of examining the locus of response biasing effects in STMM (Laabs, 1973; Pepper & Herman, 1970). During this project, I attempted to show that the preselected or subject-defined movements are better represented in memory than constrained or experimenter-defined movements and thus may be more resistant to response biasing effects (Stelmach, Kelso & McCullagh, 1976; see Appendix). In the paradigm of the second experiment the criterion movement (CM) was made under either preselected or constrained conditions while the biasing movement (BM) was always made in the constrained mode. On the basis of the relative trace strength hypothesis, a reduction in response biasing would be predicted in the preselected-constrained, CM-BM combination relative to a constrained-constrained condition. If preselected criterion movements evidenced less constant error shifts than constrained, a central locus for biasing could be inferred. However, since both preselected and constrained movements evidenced similar biasing effects, a peripheral interpretation was suggested.

Some assumptions regarding central and peripheral interpretations of response biasing effects may be outlined in the following manner. A peripheral interpretation would assume that biasing is a result of interference between the movement cues generated from criterion and interpolated biasing movement production. Such a position would require that biasing be a direct function of the overt movement cues generated. A central interpretation on the other hand, assumes that response biasing is a result of interference at some higher processing level. An alteration of biasing effects as a function of attention allocation or decision-making processes would support a central position. Interference occurring at the rehearsal or retrieval stages would likewise support a central locus of response biasing.

Three experiments recently performed during the project were conducted in an effort to differentiate between central and peripheral interpretations of response biasing. (Stelmach, in preparation; see Appendix). Experiment 1 employed a pre and post-cueing paradigm similar to Craft (1973) and Craft & Hinrichs (1971). A central interpretation would be strongly supported if pre-cueing reduced the magnitude of response biasing. Experiment 2 similarly attempted to eliminate interference effects from an interpolated biasing movement. Efficient storage of the biasing movement was disrupted since subjects were required to perform information reduction activity during interpolated movement presentation. Presumably, if the biasing movement could not be centrally encoded and stored, then no interference would be expected if biasing was of a central nature. Experiment 3 attempted to induce response biasing effects when no interpolated movement cues were generated. Evidence of biasing in this situation would provide strong support for a central interpretation. The results of all three experiments generally supported a peripheral interpretation. In Experiment 1, pre-cueing the subject as to which movement to attend failed to reduce response biasing. Presumably the subject had the opportunity to differentially focus attention on the criterion movement and to directly forget the biasing movement. It is possible, however, that subjects may have been encoding or attending to the to-be-forgotten movement. In Experiment 2, movement cues to an interpolated biasing target were also generated but storage was assumed to be blocked by high information load, interpolated processing activity. If the central processor is occupied during biasing movement presentation then interference would not be expected if the biasing locus was central. This effect also did not materialize even though it was found that reproduction of the biasing movement was severely disrupted.

Thus, in Experiments 1 and 2, movement cues to the interpolated target were generated but the experimental manipulations attempted to reduce biasing by cueing subjects as to which movement was to be reproduced (Exp. 1) or by preventing biasing movement storage (Exp. 2). The third experiment attempted to induce response biasing in a situation when no movement cues were generated. After criterion presentation, subjects concentrated on an interpolated location which was well represented in memory instead of actually moving to the interpolated location (Imagery). A movement group, in which subjects actually moved to both the criterion and biasing targets, served as a control. If directional error shifts were found with the Imagery technique, it would be strong support for a central locus for biasing since no peripheral movement cues were generated for the interpolated movement. The results supported a peripheral mechanism in that no biasing occurred in the Imagery condition. Thus taken together, the evidence points to peripheral mechanisms or overt movement cues involved in response biasing effects rather than central mechanisms. However, more experimentation is needed, especially in trying to manipulate the central and peripheral components of movement. In the next section attention is shifted to experiments performed in my laboratory which have been designed to uncover some central agents of motor control and memory.

Educational Implications. It has been known for many years that movements are susceptable to interfering activity. This part of the project attempted to examine the specific causes of this interference. The suggestion from these studies is that interference is of a peripheral origin. While it is difficult to generalize, if these findings hold up to extensive scrutiny, the implication is that movement per se causes response biasing and that movement should be kept to a minimum during learning. The amount of central involvement associated with the interpolated movement appears to cause minimal interference. The implications for the teaching of motor skills are obvious.

B. Central Components

1. Preselection. One important contributor to movement retention not necessarily exclusive of peripheral information is prior organization of a movement. A number of recent studies have demonstrated that a planned or preselected movement is better reproduced than a constrained movement (Jones, 1974; Marteniuk, 1973). In the preselected condition the criterion movement is defined by the subject and thus has the ability to predict the consequences of the movement prior to initiation. The above findings can be interpreted as support for the corollary discharge hypothesis (Teuber, 1974; Sperry, 1950). This hypothesis states that in preselected movement production the central nervous system sends information from motor to sensory centers preparing them for the sensory consequences of the movement. Thus, corollary discharge is unique to active, preselected movements and possibly allows the central nervous system to efficiently encode the proprioceptive information. The foregoing interpretation is less extreme than proposed by a number of other investigators (Festinger & Canon, 1965; Jones, 1974; Lashley, 1917; 1951; MacNeilage & MacNeilage, 1973) who have suggested that when the central nervous system can predict the characteristics of the motor act afferent information does not play a dominant role.

A recent series of studies by Jones (1972; 1974), for example, suggests that proprioceptive feedback is of little importance in movement coding. Borrowing from Taub and Berman's (1968) terminology, Jones has argued that the central monitoring of efference (CME) is the primary determinant for retention of simple motor responses. According to Jones, when a subject makes a voluntary movement "as rapidly as possible," the resulting efferent discharge is centrally monitored and stored as an efference copy (von Holst, 1954), which is thought to be a motor memory storage system operating without the requirement of peripheral feedback. The support for

Jones' central monitoring of efference (CME) comes from the finding that subjects can duplicate voluntary movements (subject-defined) more accurately than constrained or passive movements. Under the latter conditions, where the subject moves to an experimenter-defined stop, it is argued that the subjects are dependent on joint inflow since they lack the opportunity to make a preset movement. Thus, because proprioceptive feedback has "no access to central mechanisms" (Jones, 1974, p. 38) memory loss occurs.

While Jones' hypothesis raises some important theoretical issues, it fails to accomodate much of the literature in short-term motor memory (STMM) indicating that terminal location information can be retained under constrained conditions (Laabs, 1973; Marteniuk, 1973; Keele & Ells, 1972). In addition, and contrary to Jones, interpolated processing activity during a retention interval leads to an increase in reproduction error, suggesting that maintaining location aspects of movement in memory requires central capacity.

One of the main arguments for CME as opposed to proprioceptive location cues rests on the finding that subjects duplicate movement extents (i.e. distance) equally well from variable and constant starting positions (Jones, 1974). Hence, as long as the efferent commands for movement extent are the same for criterion and recall movements no deficits in motor reproduction occur, regardless of initial starting position. But what happens when the subject is forced to generate a different efferent output at reproduction from that employed in the criterion movement? This question provided the impetus for a recent series of experiments performed in my laboratory (Stelmach, Kelso & Wallace, 1975; see Appendix).

The first experiment of the series examined the reproduction of either the endpoint or the distance of a rapid voluntary (preselected) movement. It was argued that the former condition, by rendering distance unreliable would require the subject to alter the efferent output for the reproduction movement. According to Jones' (1974) hypothesis, this procedure should result in less accurate reproduction, while distance reproduction should be superior since the motor outflow for movement extent remained a reliable cue for reproduction. The results militated against the Jones' hypotheses; the location condition evidencing relatively less variability and absolute error after a 15 sec. retention interval. This finding was congruent with studies in STMM (Laabs, 1973; Keele & Ells, 1972; Marteniuk, 1973; Marteniuk & Roy, 1972) and suggested that proprioceptive location cues were primary for accurate reproduction.

A subsequent experiment examined the latter interpretation by comparing location reproduction under preselected, constrained and passive modes; the rationale being that if location cues were primary, the response mode should not be an influential factor. However, the results revealed that providing the subject an opportunity to preselect a location prior to movement initiation, was a determining element of reproduction accuracy. A third experiment verified this and also showed that the processing requirements of preselected, constrained and passive location were similar. This finding agreed with much of the literature but was contrary to Jones' (1972) argument that proprioceptive information fails to access central processing mechanisms.

Viewed overall, our results to date refute the notion that central monitoring of efference is a "necessary and sufficient" (Jones, 1974) condition for the coding and retention of voluntary movement. They have, however, led us to an important phenomenon, which as yet seems to have escaped the theoretical attention of researchers in the motor memory and control domains. We refer to this phenomenon as "preselection," the availability of which appears to allow the subject to internally organize or "plan" his response (Gallanter, Miller & Pribram, 1960) prior to movement initiation. The role of preselection, which clearly has an overwhelming influence on our previous data, would seem to force an empirical assessment of its theoretical importance for motor control.

The bulk of studies using constrained movements have indicated that distance information unlike location fades over time and is unaffected by interpolated processing activity (Laabs, 1973). This finding suggested that distance information does not require central processing capacity and, along with physiological evidence derived from Skoglund's (1956) work, has led to the conclusion that distance cues are, in fact, "uncodable" (Marteniuk & Roy, 1972). On the other hand, a more recent study by Marteniuk (1973) has found that distance information may be retained over time and is subject to interpolated processing effects. The discrepancy between this finding and those earlier may be due to the response mode of the criterion presentation. That is, while previous experiments used constrained, experimenter-defined movements, Marteniuk's (1973) subjects were allowed to define their own movement. It may be that the coding characteristics of experimenter and subject-defined (preselected) movements are different, thus accounting for the discrepant distance findings. On the basis of Laabs' (1973) model, however, distance information should spontaneously decay over an unfilled retention interval and not be affected by interpolated processing activity. Such should be the case regardless of presentation mode. To assess these differential predictions, we examined the retention of distance information under three modes of presentation, preselected, constrained and passive (Stelmach & Kelso, 1975; see Appendix). The results showed that preselected distance information was better reproduced than constrained and passive. However, the groups were not differentiated by the retention interval manipulation. Thus although preselected distance reproduction was superior, filling the retention interval with interpolated processing activity had similar effects on all conditions. It does not appear, therefore, that preselected distance requires any more central capacity than constrained or passive distance, in spite of the fact that it seems to have a stronger representation in memory.

One further point should be emphasized from the present experiment. Constrained and passive distance reproduction were both retained over a 15 sec period and were similarly affected by interpolated processing activity. These findings are in direct contrast to those of Laabs (1973) and suggest that even constrained and passive distance can be retained over time and do require central capacity. A recent study by Diewert (1974) has shown the same result. These findings suggest that Laabs' model of two distinct storage modes in memory, one for location and one for distance, may have to be reappraised in favor of an interpretation focussing on the central representation of both distance and location cues. As Marteniuk (1973) has suggested, it may be that both cues are centrally represented, but in varying degrees of exactness.

The preselection results of this experiment and previous studies has shown it to have an overwhelming influence on memory representation. The question is, why? Clearly the notion of CME put forward by Jones (1972; 1974) is unable to account for the findings, but this may not necessarily rule out the possibility of an efference-based mechanism such as the previously discussed corollary discharge. Here the emphasis is on facilitating the coding of sensory inputs based on a predictive signal from motor to sensory processing centers.

The coding of movement has typically been confined to studies in which the emphasis has been on sensory information as opposed to central organizational processes. In active, voluntary movement, these may take the form of the "motor plan" (Gentile, 1974) being forwarded via such a mechanism as corollary discharge, to sensory processing centers where it can be compared with incoming inputs. Thus, under preselected conditions, sensory processing centers would be prepared to receive peripheral inputs, while with constrained movement this would not be possible since no prior information is available regarding the terminal locus of the movement. The operation of preselection would therefore be to facilitate the encoding of information which in turn could account for the greater central representation of preselected movements.

On the other hand, some have argued that because subjects in the voluntary, preselected condition are allowed to choose their own movements, they have more "task related" information than subjects in constrained or passive conditions. Such information may allow subjects to formulate "images" (Posner, 1967) or "plans of action" (Miller et al., 1960), which would facilitate retention (Marteniuk, 1975). These strategies would not fall within a strict definition of efference.

The principle behavioral method adopted to determine the unique role of movement information derived from central and peripheral sources has been to experimentally manipulate active and passive movement. The basic argument is simple: namely, that efferent "outflow" information is available when a subject moves actively, but is unavailable when the subject is moved passively by the experimenter or some mechanical device. Thus, a superiority of active reproduction supposedly reveals the contribution of an efference-based mechanism.

The impetus for the second experiment was therefore to isolate the contributions of the efferent component and the planning component of movement. The latter has received minimal theoretical attention in spite of its potential importance (see Miller et al., 1960, Chapter 6). Neurophysiological data indicate that the structures involved in planning a movement, and those involved in generating motor impulses (i.e., execution) are not the same (Allen and Tsukahara, 1974: 991-993); functionally, however, these components have yet to be separated in terms of their contribution to movement coding.

The second experiment attempted to differentiate the two positions by employing movement conditions which differed with regard to hypothesized outflow information (active vs. passive) but were similar with regard to preselection, i.e., both conditions could generate a potential movement strategy. The predictions on the basis of this experimental manipulation were quite clearcut. Since subjects in both the active preselected and passive preselected conditions were allowed to preselect the movement, there should have been no differences between the reproduction responses in the two conditions provided the superiority of preselection is due to the availability of a higher order cognitive plan. On the other hand, if preselection plays, for example, a corollary discharge role (which is unique to active, self-produced movement) the active preselected should be superior to the passive preselected condition, since the latter lacks the motor-to-sensory outflow which prepares sensory systems to process inputs.

The results showed that preselection was of no benefit unless the subject actively implemented his planned movement. The implication from these results was that the "higher order planning process" (Marteniuk, 1975) was insufficient in itself to facilitate retention. The addition of an efference-based mechanism operating in voluntary movement appears to be necessary. It was also interesting that the efferent component appeared to be of little use when the subject had no idea of where the terminal location of the movement was. These data supported our view that preselection may involve an internal "output" code such as corollary discharge (Teuber, 1972; Sperry, 1950) in which central information flows from motor to sensory systems presetting them for the anticipated consequences of the motor act. Thus, under preselection conditions sensory processing centers would be prepared to receive peripheral inputs. The operation of preselection would therefore be to facilitate the encoding of information.

If prior response organization facilitates movement coding, it might be predicted that preselected movements would be less dependent on peripheral inputs than constrained movements. It is my position that since in the constrained conditions subjects do not know where they are going until arriving at the target, they have no efficient output code; therefore, they should be input (sensory) oriented and benefit from exposure to the endpoint. On the other hand, in the preselected condition subjects should be less input oriented since they have an appropriate output code (efferent command) and benefit less from endpoint exposure. We attempted to demonstrate this in two experiments recently performed in my laboratory (Wallace & Stelmach, 1975; see Appendix). Experiment 1 was conducted to substantiate whether endpoint duration influences reproduction accuracy. In this experiment, subjects rested on the criterion movement endpoint of a constrained movement for less than one sec, 2 sec and 5 sec and reproduced the criterion movement immediately or after a filled or unfilled 15 sec retention interval. The results showed a clear effect of endpoint duration in that reproduction following 5 sec of endpoint exposure was significantly better than when the subject immediately released the handle. Thus for constrained movements, reproduction was more accurate the longer the exposure to the criterion movement endpoint. In Experiment 2, both constrained and preselected reproduction was compared as a function of the three levels of endpoint duration used in Experiment 1. As in Experiment 1, constrained reproduction was greatly enhanced by resting on the criterion movement endpoint for longer durations. However, preselected reproduction was only marginally affected. Thus it would appear that knowing the movement in advance allows for better encoding of peripheral information, a finding consistent with the corollary discharge hypothesis.

Since prior organization of movement seems to occur in preselected production, an obvious question to ask is whether response organization occurs prior to the production of the reproduction movement. That is, is some time required to organize a reproduction movement. One way to test this notion is to engage the subject in an attention demanding task during the retention interval and vary the time allotted for response organization following the cessation of activity. If preselected movements require more time to reorganize a reproduction movement than constrained, then the duration of time following the cessation of a rehearsal prevention task should be a potent variable. The findings of a study performed in my laboratory (Stelmach, unpublished; see Appendix) suggested this possibility. Preselected or constrained movements were reproduced either immediately or 3 sec after a 15 sec filled retention interval. Only preselected reproduction was aided by the 3 sec time period prior to reproduction suggesting that preselected response organization occurs to a greater degree than in constrained movements.

Educational Implications. Typically, physical educators attempt to improve both learning and performance by focussing attention on proprioceptive cues and awareness. It may well be that certain tasks need to be taught with attention to such feedback information. However, a perusal of the physical education literature fails to reveal any consensus as to the contributions of proprioception in the acquisition and control of movement.

The results of this series of experiments suggest that useful information is available to the performer prior to movement. It seems feasible, therefore, that the performer's attention should be focussed on what he/she intends to do, rather than merely directing attention to the sensory concomitants of the completed act. Thus, it may be a more efficient teaching strategy to establish internal models of correct performances as opposed to stressing the utilization of proprioceptive feedback. An example of such an approach is the Suzuki method of violin teaching (Pronko, 1969). Auditory templates or images are laid down in memory early in the child's life. At a later time when the child begins to play the violin, performance may be facilitated because the expected sensory consequences of correct performance are known.

FOOTNOTE

[1] This technique involves the application of a sphygmomanometer cuff to the upper arm, the pressure of which is maintained above S's systolic blood pressure (180mm.Hg.) thus rendering the limb ischemic distal to the cuff (Laszlo & Bairstow, 1971a).

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