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The major theoretical accomplishment of this research effort is the application of organizational concepts derived from control theory to models of motor control. Experimental results of this effort include - 1) a demonstration that there is genuine interactivity of two limbs under a number of bimanual conditions, (2) evidence that rapid error corrections are dependent on efference rather than on afferent input indicating the existence of internal feedback that monitors efferent commands, (3) descriptions of spatial

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orientations within egocentric space, and 4) specification of the role of organizational processes in motor learning and control.

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# Part I

# Control Theories in Motor Behavior

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# INTRODUCTION

In this paper we briefly discuss the recent shift in motor control toward a theoretical orientation that views the human behaving system in a more complex manner than has been prevalent in the past. The case is made that modern control theory offers explanations and guidance in developing, comparing and evaluating models of movement coordination and regulation. To offer such explanations and guidance is justifiable given the extremely large interest in motor behavior and control that now exists. One common criticism of the completed research in the field--and one which has been made as often by those attempting to derive practical utility from empirical data (such as skill instructors and teachers) as anyone else--has been its nondirectional and incompletely conceptualized nature. Those involved in research now are being urged to avoid narrow and/or shallow conceptualizations, and control theory is offered as an appropriate alternative approach. Admittedly, control theory is characteristically apractical, it makes no immediate claim to offer instructors or other practitioners any method by which skilled performance can be acquired more quickly or retained longer. Its address is to the researchers in motor control not because the practical aspects are unimportant or trivial, but because if the research efforts are not linked conceptually the very basis for effective skill learning or instruction may be jeopardized.

The bulk of the paper, then, will be devoted to the introduction and research application of those organizational concepts derived from control theory and to the classification and critiques of models of motor control. The review closes with a discussion of the potential benefits of control theory application within different levels of scientific inquiry.

When viewed mechanically, the human organism is a multisegmented system whereby movement of one segment can influence the motion of an adjoining segment in a variety of ways. The plasticity, flexibility, and intricate organization of an acting human presents researchers with a complex, multilayered puzzle possessing countless pieces and combinations. After many years of attempting to simplify motor behavior through reductionistic paradigms, awareness has come that this form of scientific inquiry may detract from the integrity of the system being studied, and that complex behavior may not be understood as a simple extrapolation of the properties of its elementary components.

Not too many years ago, the motor behavior area was riding the wave of enthusiasm accompanying the shift from product to process oriented paradigms. The thematic shift was triggered by the belief that unravelling the mental processes which underlie behavior would help explain motor learning and performance. For many years, motor learning and memory received an impressive amount of theoretical and investigative attention (Admas, 1971; Schmidt. 1976a; Stelmach, 1974). Over time, the realization came that the study of skill learning contributed little to understanding motor acts when so little was known about the control of movement. Consequently, the popularity of these topics diminished. With increasing frequency, researchers became aware that many of the 'keys' to understanding learning and performance lies in the complexity of the central nervous system, and that without knowledge of the mechanisms underlying performance, the expectation of developing general learning principles will remain small. Thus, investigators in skill performance began turning toward motor control problems in order to better acquire an understanding of the processes and mechanisms which regulate motor acts.

Motor behavior researchers have, in the past, been primarily concerned with controlling input in order to obtain knowledge about movement control. However, it has become clear that the passive, psychophysical techniques used to examine motor information have failed to account for the fact that the active components of the performer play a major role in motor coordination. Sperry (1952, 1976) has repeatedly remarked that analysis of the motor output should tell us more about internal mental processes than analysis of the input (Kelso & Wallace, 1978). Consequently we see greater attention to and finer analysis of response characteristics in explanations of the control of movement. A derivative of this development was the utilization of more diverse dependent variables. Movement kinematics, electromyography, and evoked potentials are frequently reported and interpreted along with the traditional performance measures such as accuracy and response time. These additional variables provide descriptive information to enhance explanatory powers and/or provide additional control of extraneous variables.

As skill performance research began to focus on the control of movement, considerable theorizing and debate arose around the various types of information used by the central nervous system in the generation and coordination of movement. Much of this work was aimed at clarifying the interaction between what may be termed the central commands from the brain and the sensory feedback from peripheral receptors. As a consequence, a debate developed over the dominant sources of information for movement regulation; whether central commands were sufficient for accuracy control or whether sensory information was also necessary (Laszlo, 1966; McCloskey, 1973; Taub & Berman, 1968). While this question has broad ramifications for control theory, the major issues of concern were kept at a rather

restricted level. The centralists repeatedly demonstrated the ability of organisms to perform certain types of motor acts in the absence of feedback and the peripheralists repeatedly demonstrated performance decrements when feedback was manipulated (Glencross, 1977; Schmidt, 1976a; Stelmach, 1979). It became obvious that neither a central nor a peripheral explanation in isolation could deal adequately with all the phenomena observed. The arrival of this debate at an impasse is illustrative not only of the complexity of the motor system but also of the inefficacy of the traditional methods and has encouraged the development of more sophisticated models to depict motor control.

Two phenomena classically cited to illustrate the complexity and diversity of the human motor system, and which theories of motor control must ultimately explain, have been identified as the degree of freedom problem and context-conditioned variability (Bernstein, 1967; Turvey, Shaw & Mace, 1978). The possible movement combinations of which the skeletal joints are capable engenders the first problem. Simply stated, a degree of freedom is allotted to each linkage in the skeletal system capable of independent motion. Given that each linkage has the capacity for variable settings or ranges of motion, the number of possible combinations for the system increases exponentially. LaBerge (Note 1) provides the example of striking a piano key with a finger. When considering that there are three joints on the finger, each operated by an agonist-antagonist muscle combination capable of variable velocities to control force and placement of the finger, it is apparent that the movement parameter combinations that must be controlled are quite large. The magnitude of combinations becomes astronomical when movement encompasses the entire hand.

Context-conditioned variability is illustrated in the nonspecificity of muscle commands. That is to say, the same or a similar movement pattern can be attained through the use of several different muscle combinations. For example, individuals retain the same unique style of writing whether writing with a pen and paper or with chalk and board (Greene, 1972; Merton, 1972). It also has been demonstrated that intelligible speech can be produced when the articulators responsible are obstructed, requiring the use of different vocal tract configurations to achieve the desired phonation (MacNeilage, 1970). This complexity and plasticity is difficult to account for with relatively simple control models that postulate the programming of coordinated movement in terms of individual muscles.

These paradoxical control problems suggest a need to reassess traditional views of how coordinated movements are controlled. The major task at hand is to assimilate the rapidly accumulating new theoretical perspectives and evaluate their explanatory power. The adoption of a conceptual framework which encompasses more diverse aspects of the behaving system will aid in this endeavor.

## A CONTROL THEORY PERSPECTIVE

One framework useful for understanding the theoretical positions emerging is that of control theory which originated in systems analyses (Powers, 1973; Toates, 1975; von Bertalanffy, 1973). Control theory can be viewed as a methodological or operational paradigm focusing on the interactive behavior between or among the components of the physical system; where a system is defined as an interconnection of components forming a configuration to provide a desired response (Metz, 1974). A control theory

perspective aids in conceptual thinking and provides a basis for constructive criticism and functional evaluations. It constitutes more than simply a methodology; it is an ideology for studying 'how things work' and by its nature draws on many disciplines for application.

There are several facets of control theory which recommend it as a framework for understanding skill performance, and motor control in particular. First, an increased awareness of the complexity inherent in the control of action has served to demonstrate the inadequacy of many simple models in the literature. Such models viewed the action system in a narrow aspect and dealt with complexity by neglecting it (Neisser, 1976; Shaw & Bransford, 1977). The control theory perspective, however, is capable of representing the entire system and incorporating its complexity while, at the same time, refining it to a more digestible quality.

Second, control theory is not peculiar to any one discipline; its utility is universal where physical systems are identifiable. The increased interest in motor control from several areas of research (neurophysiology, theoretical biology, kinesiology, psycholinguistics, artificial intelligence, and the computer sciences) requires that researchers interpret widely disparate data. The common language provided by control theory promotes and facilitiates this interdisciplinary exchange and the awareness that the principles educed are not necessarily dependent on the physical nature of the system. It furnishes a superstructure for interpreting and comparing input from a multitude of sources.

Third, modelling procedures in control theory offer investigators a certain latitude and flexibility in describing systems by means of established conventions within an organized framework. Perhaps the greatest freedom is the arbitrary specification of the system boundaries. With this freedom, one may divide the object of interest into a number

of subsystems, depending on the detail of the scope required. Similarly, inputs and outputs may also be flexibly defined according to the variables of interest and can even overlap to the extent that the output of one system may provide the input of another system. It is also possible to incorporate and analyze multiple variables or signals within the same model, permitting the representation of complicated and involved operations. (For a more comprehensive coverage of control theory see Milsum, 1966; Dorf, 1974; Toates, 1975; and Carpenter, 1977).

## Control Classifications

In this chapter, discussion is delimited to volitional movement except where noted and will primarily focus on control processes beginning once the movement is selected and continuing through response initiation. In this context of volitional movement, we assign intention the highest level of control or, in systems terminology, intention is thought to provide the reference value of the system (desired goal). It should be noted here that those processes contributing to formulation of the reference value are those processes commonly represented in information processing models as perception, recognition, decision, and so forth. The results of these processing stages. including access to memory, determine the desired movement for intended action. Emphasis is placed on those processes mediating the output relative to the intended movement. Neglect of information processing stages is not intended. However the boundaries of the action system we wish to consider extend only from intention to execution of the movement. Consequently, the figures (1, 2, 3 and 4) depicting types of control present these stages as simply input for the formulation of movement intent. Although there is always the possibility

of error at any of these information processing stages, once the plan for action is selected, the reference signal, which specifies the desired performance for the system, is determined. It is relative to this value that feedback from the response is compared to determine error. Error is nonexistent when the reference signal coincides with the system's output (Toates, 1975).

When classifying models according to their organization, direction of control is a characteristic commonly used in describing controlled systems. Most control models fall into a category defined as hierarchical. Here, higher centers exert control directly or indirectly on lower structures or mechanisms. Control in the hierarchical sense can also be characterized by the degree of specificity of the command. At a very high level, intention is in a general, abstract form such as 'leave the room'. The number of ways to 'leave the room' requires increasing specificity and concreteness as the command is formalized. In contrast, direction of control in a heterarchy is not unidirectional and lower structures may control higher centers (Turvey et al., 1978).

The second categorical distinction is related to the number of levels of transformation information must pass through between the system reference signal and the achievement of the goal state. A transformation in this sense should be thought of as both refinement, as in increasing specificity, and alteration due to additional inputs at other levels. For simplicity's sake, the number of levels a system may possess has been dichotomized into single-level (one transformation) and multilevel systems (more than one transformation).

Still a third trait operationally distinguishes control processes into a meaningful dichotomy: lumped versus distributed control. This particular distinction focuses on control within a level of the system

defined. The descriptor, lumped control, is derived from the nature of systems bearing the same label. In such systems, the units comprising the system assume a uniform value for the variable describing each unit at any one time (Milsum, 1966), just as gas pressure assumes a uniform value throughout a container, regardless of its shape. In a similar fashion, systems where control processes or functions are homogeneous across structures at any one level, are termed lumped. Specifically, lumped control is demonstrated where functioning is constrained to one type of structure, although many structures may be in operation at one level. An example of a system where processing is depicted as lumped can be seen in most information processing models (Marteniuk, 1976; Massaro, 1975; Welford, 1968). In such a model, one structure is posited to operate on input at any given level.

In a distributed control system, function at any one level of the system is spread or distributed among a number of structures which may interact to achieve the desired output (Arbib, 1972, 1975, 1980a, 1980b). In a system where the value of control variables are determined by combinations of structures, several alternative combinations must exist to arrive at the same goal. A benefit of this type of control is a plasticity and flexibility, manifested in resiliency to disruption, in control function. Incapacitation or disturbance of one level need not disrupt the system since subsystems may then cooperate to compensate for the injury.

An example of distributed control is seen in the context of industrial control systems, where a hierarchy of loosely coupled computers manage the optimization of production (Kahne, Lefkowitz & Rose, 1979). In such a system, the first level of control consists of several interacting

computers responsible for maintaining local variables at levels consistent with local objectives and constraints. A second level of computers coordinate the actions of low level computers and communicate with still higher level computers, which strive to preserve overall plant goals. In this way, control is distributed over many units, with complete control residing in none.

It is advisable to distinguish between modeling the control of a complex organism as a unity or as a number of subsystems. Previously it was stated that systems boundaries could be arbitrarily defined according to the interest of the investigator. When categorizing models, however, some ambiguity can arise where subsystems are represented by lumped models. A combination of several lumped models would yield a distributed model; and similary, a distributed model may be divided into multiple lumped systems.

The taxonomy layed out is an operational convention to aid in model comparison and evaluation. However, theories of control are somewhat dependent on the level of inquiry that they address. For example, there are theories which address the entire behaving system and those which attempt to model some discrete aspect of the system; both can possess varying degrees of complexity and detail. Regardless of the scope of their intended description, models can be classified by their control characteristics. Thus, multilevel, lumped or distributed control theories may encompass systems that vary widely in their control responsibilities; for example, the firing of a single neuron versus the regulation of a gross movement. We will first consider hierarchical systems of the single-level variety, followed by multilevel, lumped and distributed systems and conclude with consideration of a heterarchical model.

## Hierarchical Control

### Single Level Systems

Function under single-level hierarchies is usually of the lumped variety, due to the constraints and limitations imposed by the availability of a single level. Many models of skill performance fall in this category since they focus on events prior to response specification and consider the response only as a reflection of preceding processing stages. These models represent an important part of the motor skill literature, but a rather limited representation of the human as a total performance system. Hierarchical, single-level control models describe motor behavior as simply output resulting from the execution of motor commands. Figure 1 illustrates the simple directness of a single-level lumped system. Information processing provides input for formulation

Insert Figure 1 about here

of intent or purpose, in which movement parameters are selected. The behavior, skill or motor act with which we are most concerned has been reduced to representations such as 'performance,' (Singer, 1975); 'output,' (Robb, 1972); 'effectors,' (Welford, 1968); 'muscular system,' (Whiting, 1972); 'responses,'(Klein, 1976); 'muscles,' (Keele & Summers, 1976). There are limitations to such a global conception of output control processes, primarily in appreciating the complex medium of which they are a product. Perusal of the more common models reveals a great amount of space (hence interest and importance) attributed to input processing and little allocated to motor control processes.

A clear example of single-level, lumped control is the concept of

a motor program. This concept was initially used by Henry and Rogers (1960) to describe the control of rapid movements and was subsequently populari-ed by Keele (1968). Keele defined a motor program as a centrally stored, prestructured set of motor commands, where an executor or command generator issues motor commands specifying all parameters of the movement. The program is transmitted via the central nervous system and is executed presumably as it was issued.

Traditionally, the motor program concept has been described as operating independent of peripheral feedback (Keele, 1968; Jones, 1977; Marteniuk, 1976). Although this may be the case in fast, highly learned movements, a strict application of this tenet to all movements is unrealistic. Keele (1977, 1980) recently presented a more palatable version of the motor program which provides for the inclusion of sequence representation in the motor program, permitting the proper sequence of movement to be generated without feedback. When precision is required or corrections needed, allowance is made for closed-loop corrections. Feedback is thought to be useful only at the level of the executor's comparator, and therefore represents a feedback loop requiring too much time for rapid alteration of the movement in progress. However, there is accumulating evidence that feedback can be useful in much shorter time frames than traditionally thought (Evarts, 1973; Evarts & Tanji, 1976). While the generality of motor programs is limited by their rigidity, they provide appropriate descriptions for a restricted set of motor acts.

Research surrounding the motor program concept generated complex models depicting those stages of information processing which determine output (Massaro, 1975; Theios, 1975; Welford, 1968). Some early models

were in the form of verbal descriptors of those processes while others employed reductionistic means to arrive at quantitative descriptions. Recently Sternberg et al. (1978) modelled the timing of rapid movement sequences in speech and typing. Three types of processing stages prior to response initiation were introduced to explain the latency and duration of rapid movement skills. The model departs from conventional programming concepts in that the construction of motor programs is achieved through the compilation of several subprograms. The first stage consists of the locating of appropriate subprograms through a self-terminating search. The second stage is the unpacking of the constitutents of these subprograms, and the third stage is the issuing of the sequence of commands to control the subprograms. The contribution of Sternberg's model lies in the demonstration of high level assemblage of programming components during response selection. It may be argued that this view provides some flexibility over strict motor programming notions by demonstrating that motor programs are not prestructured units. While these are perhaps eloquent improvements over past programming notions, they are not directed toward explaining control of movement once the command is formulated.

In addition to motor programming notions, there are other models which fall in the lumped category. Shaffer (1976) has postulated a hierarchic theory of action which is based, in part, on response latencies. To this extent, it is similar to the previous model of Sternberg et al. (1978), but differs in the examination of error types. Examining skilled typing, Shaffer posited translations of the intention to take place in two successive stages, input and output, each with a memory buffer associated with it. The form of the command is different in each stage; that is, letter strings for input and motor commands for output. Its hierarchic nature is displayed in the flow of command from intention through stages of translation. Shaffer goes on to postulate an indexing system in each buffer

which specifies syllabic boundaries and ordinal position of letters in linear arrays. The most interesting aspect of Shaffer's expose is the evaluation and classification of errors as they occurred in the typed text. The class of errors of most interest were those errors in execution which Shaffer attributed to peripheral factors of the response. Examples of such errors were hitting two keys at once, hitting the adjacent keys, and omitting letters by a weak key strike. These errors are representative of important issues in motor control, particularly the parameterization of force and location in ballistic movements. Although Shaffer posits high-level interactions, his model does not allow modification of the motor plan once it has been formulated. Nevertheless the model provides logical explanations for the occurrence of errors, a phenomena not commonly addressed in the motor programming literature.

Currently, Norman (Note 2) is formulating a theory of action which is based on errors which occur as a result of 'slips of the mind' in everyday life. The control aspects of the model indicate a hierarchical flow of control but, as seen in previous models, the various levels of processing are seen to exist centrally. For Norman, the highest level of of control is intention, the conscious willing of an event. The intention leads to the conscious selection of a plan of action, which is assumed to be vaguely specified but represents in a gross sense the act intended. Schemata, organized memory units in the traditional sense, are viewed as sensorimotor computational units comprising the elements of the plan. Norman represented schemata as the most specific determination of action plans prior to the actual behavior and indicated their hierarchical organization. Thus, when an intention engenders a plan and a match

exists between the plan and existing schemata, schema activation automatically performs the detailed specification of the actual movement. If there is not an existing match, then the plan must be modified consciously.

Some problematic considerations exist for movement control as Norman has modelled it. First, if the intention is specified incorrectly and executed according to its specification, the feedback from the response will be incorrect by the same amount as the specification deviated from the intent. Thus, when the two, intention and feedback, are compared, no discrepancy will be detected. Second, levels of specification create the potential for a loss of information regarding the extent of the error when a high-level (gross)specification is compared to low-level error information (detailed specification). While the model possesses many levels, each operates centrally and constitutes a single-level, lumped model in a control theory perspective.

Others have used the notion of schema to expand upon the motor programming concept (Schmidt, 1975; LaBerge, Note 1) where organized memory structures represent a class of events or movements with some common characteristics (Bartlett, 1932; Head, 1920; Pew, 1974; Schmidt, 1976b). Schemata have been used to represent generalized motor programs, providing flexibility by alleviating the constraints of novelty and storage associated with conventional motor programs. While Schmidt (1975) and Pew (1974) have utilized schema notions in similar ways, Pew (1974) has been more explicit with their use for motor control.

Pew (1974) incorporated schemata, generalized sources of memory information about the organization of movement, in his hierarchic model of perceptual motor performance. Pew's lowest level of control is a simple servomechanism through which passes a stream of simple motor commands selected from the schema. His next level consists of a higher-

order sensing mechanism capable of complex pattern detection and corresponding temporal organization of motor commands. Such a mechanism would allow individuals to take advantage of signal predictability in their responding. The highest level of control, voluntary or self-initiated movement, is analogous to intention in other models. Pew (1974) posited three types of feedback, external knowledge of results, proprioception, and efference copy to provide error information to the system. On consideration of Pew's model, his levels of control would appear to be more appropriately termed levels of specification. Therefore, the model addresses the central mechanisms which provide the reference signal for the system. As such, Pew's model is certainly hierarchical with many levels of information processing but only a single level of output control.

From a control theory perspective, the schema notion provides little real improvement over the motor programming concept in explaining response output. While schema notions address constraints in memory, functional control by generalized motor programs does not alleviate the problems associated with conventional motor programming. Schema theory has also been less than satisfying in generating convincing empirical data (McCracken & Stelmach, 1977; Newell & Shapiro, 1976). Although these models possess varied levels of flexibility and sophistication in modeling response preparation, these processes occur prior to formulation of the intention. For the purposes of this review, these models are considered to be single-level in nature.

Motor programming views, where variations in reaction times reflect the programming of response characteristics, do not address the

interactive and distributed nature of the nervous system. Although this literature has contributed much insight into the preparation of movement, several anomalies and unaddressed problems exist in the single-level, hierarchical control model. Even when feedback loops are employed to adjust the motor plan for the next attempt, the complexity of the system far exceeds the explanatory capacity of the motor programming concept. Although Turvey et al. (1978) indicate that single-level control could solve the context-conditioned variability problem, given that very detailed afferent information is matched with very detailed efferent commands, it cannot solve the problem of degrees of freedom. Many have found it difficult to concede that one structure may specify the exact combination of muscles for all movements (Bernstein, 1967; Gelfand et al., 1971; Greene, 1972; Turvey, 1977). Conceptualizing motor control as a single command could potentially ignore or confound processes and effects which occur between response selection and initiation. In the sections that follow, multilevel control models, in which other processes occur between intention and output, are reviewed.

## Multilevel Systems

In the previous section the problems with a single level of control were summarized to point out the inadequacy of such models in explaining motor control. But what advantages are there to viewing motor control in a multilevel model? In single-level control, once the intended movement is specified in the form of a command, no other influences are posited to affect the control of the movement prior to its initiation. In the multilevel system this is not the case; intention is still the determinant of the course of voluntary movement but transformations of the intended command do intervene. Turvey (1977) described multilevel

hierarchies in terms of decision-making structures, stating that a high-level executive specified the fundamental goals while decisions on details were left to subordinate structures. Further details are to be specified by even lower structures until the last decisions are made by the lowest structure in the system. Thus, the burden of computation on the higher stages is alleviated by delegating minor computation and processing to lower stages (Glencross, 1980; Keele, 1980; Turvey et al. 1978). In general, the commands exerting control on the organism are unidirectional between stages. The inclusion of feedback loops should not alter the integrity or directionality of hierarchial control. Admittedly, feedback from a lower level can affect the control exerted by the higher level; the purpose is adaptive and compensatory with respect to the reference signal provided by the higher level. Thus, feedback can serve as communication between levels, but the exact pathways it may take are not well defined at this time. Whether feedback in this context qualifies as autonomous control is questionable and will be addressed later in the discussion of heterarchies.

Arbib (1972) itemized some advantages and disadvantages to multi-level hierarchical control. As mentioned previously, there is a more efficient and economical use of higher levels in the reduction of computational complexity. A byproduct of this economy is increased storage at the higher levels and more programming time available in much the same way that software conventions achieve economy in computer technology. Information flow between levels is substantially reduced in comparison to the amount of information which would be required in a single command to specify all parameters of a movement. The disadvantages,

Arbib suggests, include the loss of accuracy in a multilevel hierarchy as compared to a single command specifying every detail of the response and the reduction in the organism's possible behaviors due to the constraints imposed by a hierarchy, conceivably making it difficult to learn unusual motions or to deal with peculiar environmental changes.

Multiple levels of control have been proposed from a variety of sources. Powers (1973) argued for the necessity of hierarchies of feedback control systems by pointing out that the reference signals may change according to the goals at a specific level of organization. That is, the information contained in a reference signal at a high level would connote global goals like 'walk' whereas the same intention filtered through several levels of control might include 'extension of the quadriceps'. Shik and Orlovsky (1976) supported a multilevel control system when they concluded that some features of quadrupedal locomotion are primarily controlled by a spinal automatism producing stepping in individual limbs, whereas other features are influenced by interactions among limbs and higher centers of the nervous system. In speech motor control, Abbs (1979) advocated a multilevel hierarchy with afferent feedback operational at each level in order to explain the adjustments made to descending motor commands to compensate for variations in articulator starting positions and unexpected load changes.

Lumped Models. Lumped control systems can be identified by functioning isolated at one level of control (i.e., with only one process or structure in operation). The economy associated with multilevel systems is present whether they are lumped or not. However, lumped systems are insufficient in some ways to explain the plasticity and robustness of the human nervous system (in response to injury, for example). Communication between structures at one level is possible

through information returned via feedback to the next higher level of control. Thus, compensation cannot occur within a level which results in increased dependency on higher levels of control by lower subsystems. Disturbance or damage to one level of the system would incapacitate the subsystems dependent on that particular system for control. Although pathological disorders resulting in dysfunction are all too real, we are constantly amazed by case histories of adaption and regeneration of function after substantial neural damage.

Insert Figure 2 about here

Figure 2 illustrates the essential aspects of a multilevel, lumped system where a grossly specified intention is transmitted to a number of parallel subsystems which, in turn, control other subsystems with increasing specificity. Early on, Bernstein (1967) proposed intermediate steps between higher centers and individual muscle contractions. He suggested that movement may be specified in terms of muscle linkages; linkages being defined as a group of muscles that commonly work in synergy. This view, in one form or another, has been expressed by a number of people (Easton, 1972; Gelfand et al. 1971; Greene, 1972; Turvey, 1977).

One of the more articulate explanations of low-level muscle combinations was expressed by Greene (1972). Greene suggested a style of motor control in which subsystems possessing many degrees of freedom are governed by a central system possessing a few degrees of freedom. He cited the Russian interpretation of synergies as a possible candidate for the functional muscle subgroupings he describes as subsystems. One example of these linkages is found in the velocity ratios of the wrist and elbow during flexion and extension (Kots & Syrovegnin, 1966). The

rates of change at each joint angle were proportionally related such that consistent velocity ratios were maintained. These ratios could not be attributed to the anatomical coupling and varied between individuals. Another example comes from the work of Goldberger (1969) as Greene (1972) has reinterpreted it. Goldberger severed either the pyramidal tract, or the extrapyramidal tract, or both in monkeys and noted that the joints of the arm lost the ability to act independently. If extension were required, the monkeys could reach for an object but never grasp it since they could not flex the fingers while the limb was extended. If flexion were required, as in drawing an object near, they could bring the object to their mouths but could not release it through extension of the fingers while the elbow and wrist were flexed. Goldberger (1969) concluded that the corticospinal tract exerted an inhibitory effect on muscles to prevent contraction or to permit only enough contraction to stablize the limb. Greene suggested that brainstem - spinal pathways excite all of a set of functionally related muscles which the corticospinal pathways fractionate into components, inhibiting the inappropriate ones. When the spinal pathways are severed, the ability to dissociate the components is lost, resulting in all joints responding as a unit.

In addition to low-level muscle combinations, Greene (1972) indicated the need for the independent functions of 'activation' and 'tuning.' Activation in this sense refers to the selection of members of a critical repertoire of built-in response patterns which can approximate most movement requirements. The final adjustments are achieved by tuning through feedforward, feedback or, more likely, a combination of the two. Feedforward adjustments, which are made in response to advance information,

permit the system to approximate that state required to meet the anticipated event. One of the major purposes of feedforward is to bring the state of the system 'into the right ballpark,' or a broad class of states, wherein feedback can adjust the system to its exact required state. The preparatory tuning which may occur prior to movement takes the form of progressive change in thresholds and reflex amplitudes in the lower levels of the motor system (Gelfand et al., 1971). Further evidence of preparatory tuning is included later in this section.

Greene (1973) analogizes the generation of responses to a hierarchical multilevel 'tree' structure, in which earlier levels "compute crude, inaccurate versions of the required response, which are refined and corrected by later stages" (p. 326). Some of the advantages of this control structure in terms of system versatility are outlined by Greene. First, the refinements at each stage form the branches of a tree structure indicating which actions are related through a common precursor. Thus, minor alterations need only take place at the last common precursor. Second, the crude precursor could serve as a rapid response to emergencies in order to permit time for more precise corrections. Third, complex movements are comprised of recurring subroutines to avoid duplication of effort. The problem of context-conditioned variability may also be explainable in this multilevel structure if different branches are seen to converge on the same response output. Being one of the first to draw attention to the concepts of low-level muscle combination and tuning functions, Greene provided great impetus for their creative and innovative application in motor control.

In contrast to the notions of Greene (1972), Easton (1972) suggested that a considerable amount of motor coordination was based on a repertoire of reflexes. Muscles engaged in associated movements could be functionally connected by combinations of reflexes, or coordinative structures, which could be activated by a single command of either central or peripheral origin. The notion of coordinative structures invoked by Easton involves the pattern of connections between interneurons and other interneurons or motoneurons which resembles those patterns elicited by reflexes (Easton, 1978). He arrived at his conclusions through observation of quadrupedal gaits, human movement sequences, and other neurophysiological findings. Easton observed many similarities between reflexes and portions of voluntary movements, as have others (Fukuda, 1961; Hellebrandt et al., 1956). He suggested that in some way reflexes provide the 'words,' whose combination represents coordinated movement. In interpreting the work of Shik, Orlovsky and Severin (1966), Easton noted that as the level of surgical sectioning ascended the spinal cord, movements elicited from animals become more complete, accurate and complex. This would appear to support a multilevel system.

Easton (1978) revised his evaluation of coordinative structures to describe a loose estimation of motor programs. Movement commands, via the central nervous system, facilitate reflex centers which in turn facilitate groups of motoneurons or interneurons. Once the pathways are primed the central nervous system issues a general command of 'GO' to all motoneurons, from afferent feedback and from reflex recruitment. As Easton points out, this view of a motor program is quite different from its conventional use in the literature. However, it does present an alternative to the rigid concept that many find unacceptable (Abbs, 1979; Arbib, 1980a; Easton, 1972; 1978; Kelso, Southard & Goodman, 1979; Turvey, 1977).

There is further evidence that a small number of independent muscle groupings can simplify movements involving large numbers of muscles. These programmed combinations of muscles are posited as the external language of movement as well as the internal language of the nervous system. It is for the management of these synergies that spinal and supraspinal systems are responsible (Gelfand et al., 1971). The spinal cord's ability to produce rhythmic, fixed patterns in the absence of supraspinal influence is convincing support for the multilevel models and the complexity of this portion of the central nervous system (Berkinblit et al., 1978; Grillner, 1973; Smith, 1980; TenCate, 1964). The presence of interneuronal networks, which may be activated to produce stereotypic movements and segmental reflexes, provides evidence of subsystems capable of autonomous operation and likely candidates for the vocabulary of the organism's control language (Gurfinkel et al., 1971). The concept of functional groups of muscles, be they coordinative structures (Easton, 1972, 1978), automatisms (Shik & Orlovsky, 1976), spinal generators (Smith, 1980), motor schemas (Arbib, 1980a, 1980b), or synergies (Bernstein, 1967), is useful in attempting to describe the meaningful units upon which the central nervous system operates. They represent intermediate control levels which, when activated, appear to perform their functions autonomously.

To posit that the automatism may be activated from either central or peripheral sources appears to be a breach in the hierarchical arrangement of control. That peripheral stimulation in the absence of volition may evoke the entire coordinative structure indicates that coordinative structures constitute higher order reflexes arranged heirarchically (Easton, 1972, 1977; Shik & Orlovsky, 1976). Volitional movement could not, however, be controlled simply by piecing the stereotypic coordinative

structures together. Coordinated, volitional movement would require a smoothing or tuning function to choose and fit appropriate sets of muscles. Greene (1972) metaphorically described tuning as an attempt to approximate an unknown curve with portions of familiar curves in much the same way that a draftsman uses a French curve. Easton (1977) suggested that tuning is accomplished by the interaction of reflexes with each other and with signals from the cerebellum, midbrain, and motor cortex. While the specific pathways which could achieve tuning have been suggested (Easton, 1977; Goldberger, 1969; Greene 1972; Orlovski, Severin & Shik 1966), their activation and interaction in order to perform tuning has not been well established.

Shik and Orlovsky (1976) have isolated two intermediate levels of control in locomotion that, descriptively at least, appear very similar to Easton's coordinative structures. They include a spinal automatism controlling step cycle and a brainstem-spinal automatism controlling interlimb coordination and maintenance of equilibrium. The first level description resulted from the finding that basic patterns of stepping could be generated by the spinal cord without input from the brain and indicated an automatism located in the spine. This spinal automatism would control activity phases of muscles in the stepping cycle while the brain would influence only the overall level of muscle activity. Description of the second level resulted from the observation of interlimb reflexes and the central coordination of limbs during locomotion, indicating the presence of other higher level automatisms responsible for these events. In assuming these functions, the brainstem-spinal automatism is also held to be responsible for maintenance of equilibrium.

Where interlimb coordination is concerned, Kelso, Southard and Goodman (1979) have found synchrony between the hands in movement of varying amplitude and precision. When subjects moved one or both hands to targets which varied in difficulty, kinematic analysis of the movement demonstrated a close interactive relationship between limbs. The presence of a coordinative structure or automatism which constrains the limbs to move in synchronous patterns relative to velocity and acceleration was invoked by way of explanation. The authors argued that the brain specifies the activity of low-level automatisms to achieve the spatial demands of the task, but does not specify the pattern of interlimb coordination. Thus the temporal relationship of simultaneous movements is relegated to the automatism producing relatively invariant patterns of movement synchrony.

In another direction, though still searching for the 'language' that specifies movement, Bizzi and his colleagues (Bizzi et al., 1978; Bizzi, Polit & Morasso, 1976; Polit & Bizzi, 1979) have studied the central control of movement evoked by vision in the control of eye and head movement as well as pointing behavior in monkeys. Through disturbances imposed by loading, Bizzi et al. (1978) found that deafferentation, via cervical rhizotomy and chronic vestibulectomy, did not seem to alter the control of head positioning. Hypothesizing that muscles at the joint assume spring-like qualities and may be programmed as such (Asatryan & Feldman, 1965; Cooke, 1979, 1980; Schmidt, 1980), Bizzi imposed constant and inertial loads on head turning and limb pointing in response to visual targets and found consistent over- or undershooting. However, when the load was removed the correct position was attained. Bizzi concluded that limb trajectories were controlled through the establishment of an equilibrium point between the spring-like qualities of the agonist and

antagonist muscles and that selection of the appropriate equilibrium point was achieved by the central nervous system through specification of a given level of alpha-motoneuron activity to both muscles. Thus, the control signals of the central nervous system are in terms of the firing ratios of alpha-motoneuron activity to the agonist-antagonist configuration. The lumped nature of this multilevel model arises from the functioning of the central nervous system at some intermediate level to specify the equilibrium points. Therefore, at a particular level of the nervous system one type of function is being carried out.

Abbs (1979) recently postulated a multilevel model of speech motor control to explain speech motor equivalence and suggested that adaptive modification of descending commands triggered by feedback can take place at different levels of the nervous system. The problem of speech motor equivalence is further evidence of context-conditioned variability in a system where many different functions (chewing, breathing, whistling, and speech) are performed by the same anatomical structures. Motor equivalence in the vocal tract is observable in two conditions: individual articulatory movements which do not covary with vocal tract goals in a constant relationship; and, at a lower level, individual muscle contractions which do not covary isomorphically with particulatory movements. From these circumstances and the observations of compensatory adjustments to unanticipated articulatory loading (Folkins & Abbs, 1975, 1976) Abbs posited a three-level model with the primary output parameters being overall vocal tract configurations. At lower levels, afferent feedback is necessary for the compensatory adjustments needed to achieve the vocal tract goal, both aerodynamically and acoustically. Level one of the

model specifies the overall vocal tract configuration corresponding to the intended phonetic element. Level two determines the specific articulatory movements whose combination will achieve the first level specifications. Level three specifies the involvement of the individual muscles required for the articulatory movements programmed at level two. Abbs's model does not fit easily in the lumped class of models because compensatory adjustments are made between elements at a particular level and could be construed as distributed (due to the interactive relationships). However, if the adjustments are made at the next higher level where feedback from the lower elements is combined, the control mode would be classified as lumped. Since feedback pathways are poorly defined at this time, the finding that elements of the articulatory movements do communicate for compensatory adjustment would give this model a distributed classification.

We have described a particular type of lumped model which addresses those intermediate mechanisms intervening between intention and action which attempt to approximate the control language of the organism. At this point, we wish to acknowledge the presence of other qualitatively different models which are distinguishable by the defined boundaries of the systems they consider. One type of model presents subsystems which encompass limited portions of the organism and are most common in modelling neurophysiological structure (Boylls, 1980; Ito, 1970). Although such models would be included in the lumped category, their combined states may represent distributed control. Still a different type represents the entire organism as a lumped model. LaBerge (Note 1) recently offered a model in which motor schemas represent the high-level organization of

voluntary motor acts and control coordinative structures which operate at a lower level to control muscles directly. These variations on the multilevel, lumped model possess characteristics similar to those already discussed in this section and more detailed reviews have been omitted due to potential redundancies and space limitations. The reader should be aware of differences in the level of inquiry these diverse models represent.

There are a number of disadvantages to utilizing a lumped model to describe the entire motor control system. Major among them is a lack of plasticity and flexibility attainable when function is interactive at a given level of control. The necessity of an executive controller or 'command neuron' (Davis, 1976, Rosenbaum, 1977) also contributes to the inflexibility of the model. In some cases, the lumped model may be a simplification of a more complex, distributed model but the cost of simplicity is the elimination of plasticity and flexibility. One factor contributing to the use of lumped models is the, as yet, poorly defined neural circuitry of the system. When more is known about the interactions and interconnections of the central and peripheral nervous systems, lumped models will become less common.

Distributed Models. Distributed models, as defined earlier, possess a control mode which is diffused across several structures which interact within and between levels to arrive at an output. This type of control is considered hierarchical since the direction of control remains top-down and may include feedback. Figure 3 exemplifies a situation where high-level function is shared by or distributed across a number of structures or

collections of neurons. Notice that there is not one 'command neuron' or executor; the function of initiating action is achieved by the cooperative effort of any number of neurons or structures. Also note that communication is present within a level and between levels so that control influences may come from a number of sources. It is obvious that a system of this type has the potential to be extremely complex in operation and in understanding.

Insert Figure 3 about here

Neurophysiologists were among the first to realize the distributed nature of function in the nervous system (Davis, 1976; Nauta & Feirtag, 1979). A favored research technique in neurophysiology was that of the lesioning or ablation of specific neural areas, followed by the recording and examination of the results. The applied reasoning deduced that the lesioned area was assumed responsible for the disrupted function. As function mapping of the brain progressed, the equivocality of the findings became apparent and the interaction of neurophysiological systems and structures became the rule when attempting to identify behavioral or observable functioning. Luria (1973) described the localization in the central nervous system as "a network of complex dynamic structures, of mosaics united in a common task with successive and simultaneous activity in a number of areas required to achieve any particular function" (p. 33).

Investigators in brain theory and artificial intelligence have chosen to develop distributed models because of their capacity to exhibit complex behavior (Apter, 1945; Arbib, 1972, 1975, 1980a; Kahne, Lefkowitz & Rose, 1979; Pitts & McCulloch, 1947). Arbib has devoted much effort toward expanding the notion of distributed control. He argues that the

mechanisms of cooperative computation, rather than of executive control, operate in the brain; offering a distributed structure of cooperating systems.

One example of cooperative action is found in Pitts and McCulloch's (1947) principle of the redundancy of command in which control passes to the region with the most important information. The model was developed to illustrate functioning of the superior colliculus as a somatotopically organized network lacking an executive neuron. The model demonstrated the plausibility of action arrived at by a population of neurons, none of which possesses complete information about the environment. Thus, in cooperative computation, decision and plans are based on a 'consensus' of neuronal systems. The interaction can be interpreted either as cooperative or competitive, depending on the summative value of the individual structures. With this view, many controls systems are activated with either positive or negative influence on achieving the goal and their individual success is determined by their summation.

In the control of movement, Arbib (1980a) posits the presence of motor schemas and coordinated control programs. For Arbib, motor schemas represent the 'mutable units' of control at various levels of refinement and correspond to muscle synergies as functional building blocks of movement, a very different usage than that typical of schema (Bartlett, 1932; Schmidt, 1975, 1976). Arbib suggests that a motor schema be thought of as a control system in itself, possessed with goals, controlling action and monitoring feedback. The utility of Arbib's motor schemas, as before with coordinative structures, lies in their ability to reduce the degrees of freedom associated with movement. It is the precise combination of motor schemas which defines skilled movement and is achieved through a

concept Arbib (1980a) introduces as a coordinated control program, the purpose of which is to control the timing of the coordinated activation of a number of systems. Through this interwoven system of activation, simultaneous actions and the smooth phasing of motion is permitted. Thus coordinated control programs 'orchestrate' motor schemas to perform movement. Based on the equivalence noted in motor plans and acts (see control classifications), Arbib (1975) suggests that there can be several coordinated control programs for a particular movement, some are inherent in the neural circuitry and some may be acquired. The similarity between function of Arbib's coordinated control program and the tuning systems proposed by Easton (1978), Turvey (1977), and Greene (1972), is striking.

Arbib (1980a) posits two functions subserving tuning through feedforward control. First, feedforward in an anticipatory fashion counteracts the effects of potential disturbances. Second, feedforward may act as a strategy for 'ball parking' movement by generating control signals that eliminate large discrepancies rapidly. Similar to Greene's notions discussed earlier, evidence to support coordinated control programs was cited from Holmes (1939), who observed that when patients with cerebellar damage moved the impaired arm to a target, their program for control of the trajectory seemed to be unimpaired. However, the patients' inability to decelerate on approaching the target implicated damage to the feedforward component of the control program.

The mechanisms suggested by Arbib (1972, 1980a, 1980b) to provide input to these distributed control systems are neural maps. They are viewed as control surfaces from which the spatial-temporal patterns for movement may be derived. Neural maps used as control surfaces differ from

the common use of neural maps in the types of information they convey. The latter type of map simply correlates the input items with positions on a neural surface; knowing one will not necessarily identify any other. The former type of map provides information about the topological relationship one item shares with several others. Thus, information from one item will provide relative information about other items, suggesting a certain economy in storage and a basis for cooperative computation. It is then plausible that a 'layered motor controller' exists in which position of input on the control surface, determined by the 'center of gravity' of an array of activation points, encodes the target to which musculature will be directed. In this manner, each activation point contributes to the target determination and responsibility for the course of movement is distributed among these many points.

In a similar vein, systems and subsystems may combine cooperatively or competitively to arrive at a desired goal. The spinal cord has been viewed as one site for such interaction in its role as a complex mediator between supraspinal influences and movement (Berkinblit et al., 1978; Gurfinkel et al., 1971; Gurfinkel & Paltsev, 1965; Shik et al., 1963). Some of the Russian investigators systematically examined the communication and interactions of subsystems involved in preparing a complex, kinematic chain such as the body for movement (Belenkii, Gurfinkel & Paltsev, 1965; Paltsev & Elner, 1967). Subjects were required to stand and make voluntary arm movements, while changes in electrical activity of various skeletal muscles or of a spinal segment were monitored. Belenkii, Gurfinkel and Paltsev (1967) reported anticipatory activation of some muscles of the lower limbs and trunk involved in maintaining equilibrium, prior to the movement.

Recordings indicated that neural activity preceding movement was elicited not only from the alpha-motoneurons, but also from the interneurons of the spinal segment (Gurfinkel et al., 1971). Gurfinkel and Paltsev (1965) demonstrated the presence of cross influences in the spinal cord. A knee jerk on one side altered the state of the segmentary structures of the opposite side by evoking both patterns of facilitation and inhibition depending on the time course of the task.

It appears that supraspinal processes do not simply send direct movement commands. The basic role of supraspinal influences is the "appropriate rearrangement of the interaction organization of the individual subsystem at the spinal level" (Gelfand et al., 1971, p. 336). Thus, high-level processes which prescribe the interactions of subsystems are seen to implement feedforward and achieve tuning. It is the interactive and cooperative nature of these spinal processes that places them in the distributed category.

There is further support for the efficacy of multilevel distributed control in describing the human behaving system illustrated in a summary by Gurfinkel et al. (1971) which describes the findings of several investigators concerning the system of interactions occurring at the spinal level. It was found that a large number of descending fibers from the brain terminate on interneurons of the interstitial zone, on the ventral and dorsal horns, not on motoneurons, offering an intermediate level of control. Most of the synapses in the spinal cord are combinations of spinal neurons on one another, with a smaller percentage formed from axons coming from the brain and dorsal roots. Such synapses in combination may yield the control surfaces Arbib (1980a, 1980b) and Pitts & McCulloch (1947) refer to. The motoneurons of different muscle groups may interact to produce phenomena

such as reciprocal facilitation and inhibition. Also, there exists at the segmental level, a reflex system controlling the interaction of muscles via the muscle receptors, an example being the crossed myotatic reflexes. Mechanisms such as these latter two systems offer examples of communicating subsystems, which when coupled with supraspinal input resemble the distributed control exhibited in the computer-run factory example of distributed processing. One point clearly reiterated is that for such subsystems to achieve cooperative computation the notion of 'horizontal' interaction of neurons must be used (Gelfand et al., 1971). Horizontal interaction would seem to provide communication within a level and is reminiscent of the type of control provided by control surfaces depicted as neural maps.

Some corroborative evidence for 'horizontal interaction' and command by consensus was demonstrated by Davis (1976) in the central motor networks of invertebrates. Davis's efforts were directed toward revising some of the organizational concepts traditionally attributed to motor systems. It was thought that the properties of a motor network directly reflected the properties of single neurons within the network. Instead, Davis (1976) concluded that network properties reflect the interaction of many cells, each with a different property and has designated the results of this interaction as emergent properties. Moreover, when this concept is applied to command functions, control by a consensus of neurons is the result. Davis posited control by consensus in opposition to the notion of single command neurons which elicit complete behavioral acts. The distributed nature of these concepts in the invertebrate nervous system provide additional weight to this form of control. Davis proposed other organizational concepts which have more bearing on heterarchical control and will be included in that section.

In the previous section, lumped models were criticized for their inability to respond to local perturbations. How may a distributed system be an improvement? If the processing or computation proceeds in a serial fashion, then deletion of any one step would result in the system failing. If there are a number of lumped systems operating in parallel but with no communication (Figure 3), a system failure may be averted if there is redundancy of command to the local area affected. But in systems operating under cooperative computation (Arbib, 1975), the ability of the system to compensate for subsystem deletions due to injury or errors may be possible. The ability to compensate would be a function of how familiar subsystems are with each other. They must be able to communicate the necessary information for remaining subystems to effectively assume the deleted function (Figure 4). The system would fail only if the deleted step was located late in the processing, so close to the actual output that it could not be compensated for or corrected by cooperating systems. A model possessing these features would optimize its flexibility and explain those errors that do occur.

The advantages proffered by models of distributed control are convincing proponents. The flexibility and plasticity of such models have been repeatedly expressed herein and illustrate the adaptability of which distributed control is capable. The resistance to failure (failure, in this case, of the entire system) adds reliability to the list of advantages. Finally, multilevel models may provide the basis for explaining transfer of skill, where an abstract representation of a sequence of action in the environment can be implemented by entirely different muscle groups (Keele, 1980).

There are disadvantages to distributed control which may detract from its optimality and yet add to its veridicality. When control is centralized through a high-level controller with all information available, better performance results relative to specific situations and purposes. However, this achievement is at the cost of flexibility, reliability and an extraordinary increase in responsibility of the single controller. When control is decentralized, as in a multilevel, distributed model, greater flexibility is achieved through interacting systems, but there is also potential for errors with each interaction, much like residual noise in the system. Such noise would increase the variability of the output and could explain the observation that humans never perform a task exactly the same way twice (Bartlett, 1932; Bernstein, 1967; Schmidt, 1975).

Perhaps the greatest disadvantage to the concept of distributed control is the difficulty one encounters in trying to study it. The possible interactions and potential sources for input present the investigator with a Gordian knot, difficult to unravel and difficult to retie. Phenomenologically, convincing parallels have been identified between the human nervous system and this type of control. Thus, control processes modeled as a multilevel, distributed system would seem worth the effort of examination. The next class left to consider, heterarchies, bears many similarities to the present model.

## Heterarchical Control

The theoretical application of heterarchical control to motor skill performance is a recent development (Davis, 1976; Turvey, 1977; Turvey et al. (1978). Its formal statement has also spawned the development

of additional control principles such as coalitions (Turvey, 1977; Turvey et al., 1978) and unique applications of the equation of constraints (Fowler et al., 1978), as well as reemphasizing previously established concepts such as affordances (Fitch & Turvey, 1978; Fowler & Turvey, 1978; Gibson, 1977). The concept of heterarchical control in the area of artificial intelligence is used to indicate a condition in which A can control B at one level and B may control A at another level (McCulloch, 1949). It can be seen that the direction of control in a heterarchy is not immutable, as it is of hierarchies (Figure 4). Lower-level systems may control or dominate high-level systems, and communication between systems is present, although indirect in some cases (E has knowledge of F through B).

Insert Figure 4 about here

Turvey et al. (1978) distinguished heterarchies from the hierarchies defined earlier in this chapter. First, the relation between any two systems is that of free dominance. In other words, the flow of information between the two is reciprocal. A second feature of heterarchies is that of functional pluripotentialism, which maintains that a portion of the system is not restricted to any one function and can perform a number of functions as the environment demands. This feature is in opposition to the strict, unitary roles Turvey et al. (1978) ascribed to hierarchies. A result of this quality is executive management through cooperative functioning of several systems. The combination of features attributed to a heterarchy also contributes to the decentralization of control, an overwhelming theme in the literature concerned with this model and the previous one.

In a heterarchy, the presence of loops creates a state of circular transitivity of dominance. In essence, the system is closed-loop in

nature and as such is sensitive to perturbations in the environment. If the heterarchy is limited such that control can only be exerted on adjacent systems (Figure 5) a 'province of ignorance' (Turvey et al., 1978) is created which purportedly optimizes control by preserving a homogeneous distribution of pluripotentiality. Therefore, no system is more central than any other, which denotes relative autonomy among the systems. Turvey et al. (1978) posit that this circular transitivity and the accompanying autonomy of systems contribute to the solution of the context-conditioned variability problem by decreasing the unequal spread of pluripotentialism.

Some of the organizational concepts posited by Davis (1976) to describe the central motor network of invertebrates incorporate some of the concepts Turvey et al. (1978) ascribe to heterarchies. Davis describes four classes of nerve cells to comprise the neuronal networks of motor control: the command, oscillator, coordinating and motor neurons. In the past the functional roles of different neurons were considered mutually exclusive or compartmentalized. However, it can be shown that individual neurons may perform more than one functional role; for example, a command neuron may act as an oscillator. Thus, some evidence is found for 'functional pluripotentialism' as Turvey et al. (1978) have termed it. Davis refers to this aspect of neurons as distributed function, which differs from the way the term has been used in this chapter. The direction of control is not immutable in Davis's revised organizational principles. In opposition to the strict notion of unidirectional, hierarchical networks, the concept of reciprocity is posited in which extensive reciprocal interaction between different classes of neurons exist, thereby displaying a heterarchical type of control.

The problems of context-conditioned variability and degrees of freedom are the major targets for explanation by those advocates subsumed

under heterarchies. In reviewing the manifestations of these problems, the conclusion is reached that the motor apparatus cannot be regulated solely by efferent impulses generated at a high level. The approach favored by Turvey et al. (1978) to address these problems is that of coordinative structures. This collective of biokinematic variables is defined as a "group of muscles, often spanning several joints, that is constrained to act as a unit" (p. 563). Turvey joins company with several theortists (Bernstein, 1967; Easton, 1972; Fowler & Turvey, 1978; Kelso et al., 1979) in the use of coordinative structures to serve as the vocabulary of motor control. The tuning function present in other accounts, takes place in two prescriptive dimensions (Boylls, 1975). The structural prescription is the ratio of activity in the muscles of the coordinative structure or its 'dynamic topography.' The metrical prescription acts as a scalar quantity to govern qualities like speed. The specification of these two quantities is what constitutes tuning. It is suggested that the cues responsible for tuning coordinative structures originate primarily in the environment and are tapped through perceptual sources. The appeal of coordinative structures for incorporation in a heterarchy, as they have already been incorporated in hierarchies, is the prospect that they perform as a relatively autonomous unit at any level of complexity (Turvey, 1977) and serve to constrain the degrees of freedom.

There is no consensus in the literature for the classification used by Turvey. Arbib (1975) does not limit a hierarchy to systems with fixed roles but arrives at conclusions similar to those of Turvey et al. (1978) regarding cooperative management. However, it should be pointed out that a hierarchy with feedback loops (Abbs, 1979; Easton, 1978) would, according to Turvey, be designated a heterarchy. The role of feedback in

a controlled system is in question here. Feedback in a simple system constitutes information corresponding to the success of the system in achieving its goal as specified by the system's reference signal (Toates, 1975). Superficially, one might be tempted to list its purpose as the elimination of error from the system. In actuality, the purpose of feedback is to generate error; error being defined as that information conveying the difference between the reference signal and the output of the system. Thus, the only influence feedback exerts in a control sense is relative to the higher command of the reference signal. Whether the distinction is important enough to warrant a separate classification for heterarchies is debatable. The problem is largely one of semantics and the need for a more universal taxonomy.

Although, theoretically, the model is weighty and controversial, at this point is is empirically weak, having little concrete experimental support or detraction. Consequently, distinctions and conclusions expressed do not seem to have advanced the body of knowledge far. However, the theory is at an early stage of development where definitions and classifications are still being operationalized. Some major points are similar to concepts forwarded by previous theories and have been incorporated into a new framework. The statement of a theory of action based on heterarchical control has generated much thought and controversy in the area of motor control. It illustrates the trend toward broader approaches to theorizing and the incorporation of ecological concerns.

## CONCLUDING REMARKS AND PROSPECTS

Within the past decade the role of the central nervous system in motor control has been studied in relation to acts ranging from simple reflexes to complex, voluntary movements. The data base for the motor

control area has expanded as procedures, paradigms and theories have developed and proliferated. The present report is an attempt to provide a conceptual framework for documenting the various types of control models which have been used to account for motor control. Some of the benefits to be derived from viewing motor control theories in this framework were outlined and a classification scheme was presented to discriminate between models based on their different forms of control. Through a systematic review and categorization those properties, either inherent or emergent, which may enhance or detract from each model's explanatory power were distinguished.

It was observed in many cases that the choice of model type was restricted by current experimental technique; that is, technology has not advanced far enough to provide complete and exact answers to questions concerning control pathways. This restriction has contributed to the presence of two undesirable conditions. In this review, *models*, primarily because of their imprecise formulations, may have been placed in categories which seem inappropriate. Accordingly, as progress is made, control theories should evolve toward veridical presentations. Moreover, these restrictions have often forced investigators to develop analogical and metaphorical arguments in lieu of strong empirical data. Analogies and metaphors provide an excellent means of communicating and illustrating concepts. However, they are a weak form of explanation and should not be used to document or corroborate theoretical premises.

Throughout this review there have been a number of recurring ideas which illustrate a consensus for the necessity of certain control conventions. Mechanisms serving the same functions and fulfilling similar purposes appear repeatedly under different labels. The first consists of a low level collective of movement patterns proposed to constrain the degrees

of freedom. Thus, in all multilevel models, units of movement are postulated: coordinative structures, spinal automatisms and generators, synergies, and so forth which act to ease the burden of computation on higher levels. Conjointly, a tuning mechanism is commonly postulated to piece and organize these low-level collectives into whole, coordinated movements. Certainly, future investigations should and will be aimed at discovering and defining the sites of control for these mechanisms.

Further, it appears from the preceding discussion that there is a trend toward delegating greater control responsibility to progressively lower levels. Consequently, single-level, lumped models of movement control have less explanatory power when dealing with complex behaviors in a dynamic environment. Moreover, recent neurophysiological findings (Davis, 1976, Gurfinkel et al., 1971), describing the organizational complexity of the nervous system (e.g., signal input and interactions occurring at different levels), render this model implausible.

Motor programming views, represented here as single-level, lumped control, have contributed much to the knowledge of response preparation. Reaction time methodology is certainly a powerful tool for examining preparation processes, but seems to lack the resolution to definitively address those problems of control discussed here. The meaningfulness which can be attributed to those processing stages represented by variations in reaction times is suspect in a multilevel system, particularly in the case of motor equivalence. There are several classes of equivocalities in which the relation of functioning and innervation of a muscle may produce idential movements, while in the same vein, identical descending commands produce different effects on the segmental motoneurons depending on their state at the time (Aizerman & Andrejeva, 1968; Turvey et al., 1978). This type of interaction and equivalence forces

one to take a cautious view of conclusions concerning initiation and duration parameters in response programming analyses. The implication is that it may be desirable for motor control investigators to move toward experimental situations which integrate kinematics and electrophysiological measures.

A system as complex as the human nervous system should be analyzed and conceptualized at different qualitative levels. Marr and Poggio (1977) specified four important levels of understanding related to the object of scientific inquiry, equated here with the human motor control system. At the first level, investigation centers around the basic elements and components comprising the motor control system - neurons, muscle fibers, motor units, etc. The second level is that of the mechanisms, combinations and composites of the basic components which act to perform specific functions. Examples would include sensory transducers, reflexes, and synergies. At the third level is the algorithm, describing the interaction and coordination of mechanisms. Sensorimotor integration, some schemata notions, and cerebellar and cortical control of movement would all be representative of this level of inquiry. Finally, the last level is that of theory, the set of principles which govern the interactions of a collection of algorithms. There are logical and causal relations among the levels and the four levels of description will have their place in the eventual understanding of motor behavior. However, the important point is that the four levels of description are only loosely related (Marr & Nishihara, 1978) and have most often been studied independently.

Individual disciplines often pursue research confined to one level with little consideration for other levels. Appreciation for the complexity, and we believe understanding, requires attention to the logical and causal relations between levels. Arbib (1972) recommends that "...a scientist

who works on any one level needs occasional forays both downward to find mechanisms for the functions studied, and upward to understand what role the studied function can play in the overall scheme of things" (p. 10). In the motor control literature, information available at a particular level can support the findings of another, while generating further research at either level.

To successfully accomplish the interaction between levels of inquiry and disciplines, individuals will require a broader background in a number of areas. A functional understanding of key concepts from a number of disciplines studying the biological and behavioral determinants of movement is necessary. As illustrated in this review, behavioral models have changed in accordance with discoveries in supporting disciplines, and students of motor control and skill performance should be prepared to take advantage of progress in each related discipline.

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# FIGURE CAPTIONS

Figure 1. Figure 1 presents the hypothetical flow of control information in a hierarchical, single-level lumped model. In this figure, the element of the model designated as "Information Processing" represents the resultant, non-motor perceptual and decision processes which occur prior to formulation of the intention. Intention leads to the detailed computation and specification of the parameters of the movement by a response generator (element A) which is then transmitted to the effectors (element B) leading to output, where A and B represent functional units in a control system. Feedback loops are not represented here as control pathways since the value of their information is dependent on the reference signal or intention.

Figure 2. Figure 2 represents the hypothetical flow of control information in a hierarchical, multilevel, lumped model. The abstractly formed intention is initiated by element A and transmitted to a number of parallel subsystems (element B) which in turn control other subsystems (elements C) with increasing specificity, until movement is achieved.

Figure 3. Figure 3 represents the hypothetical flow of control information in a hierarchical, multilevel, distributed model. In such a model, executive function is distributed across a number of structures. It is the interaction or combination of these structures that contribute to the control signal and ultimately the movement.

Figure 4. Figure 4 represents the hypothetical flow of control information in a heterarchy. Intention in a heterarchy can be carried out in a variety of ways, A controlling B, etc. However, a heterarchy possesses the additional flexibility of altering the direction of control such that B may also control A. Thus, the presence of loops creates the state of circular transitivity of dominance.

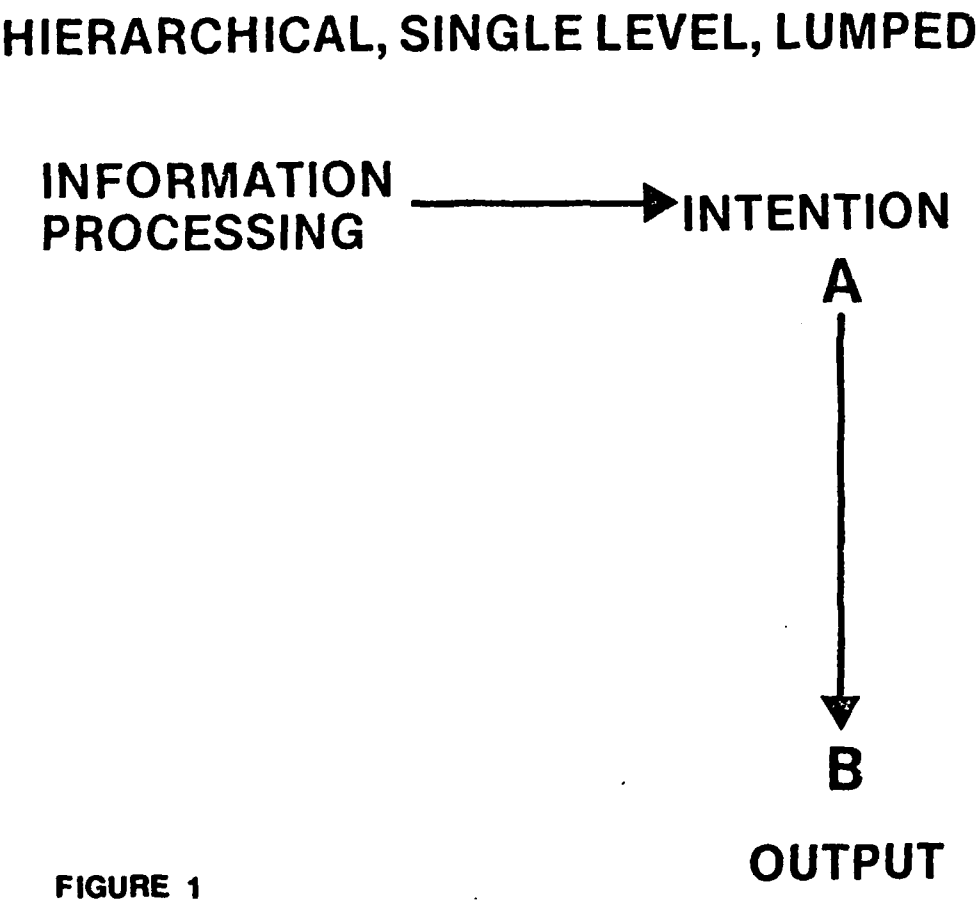

HIERARCHICAL, SINGLE LEVEL, LUMPED CONTROL
INFORMATION PROCESSING
INTENTION
A
B
OUTPUT

FIGURE 1

# HIERARCHICAL, MULTI-LEVEL, LUMPED CONTROL

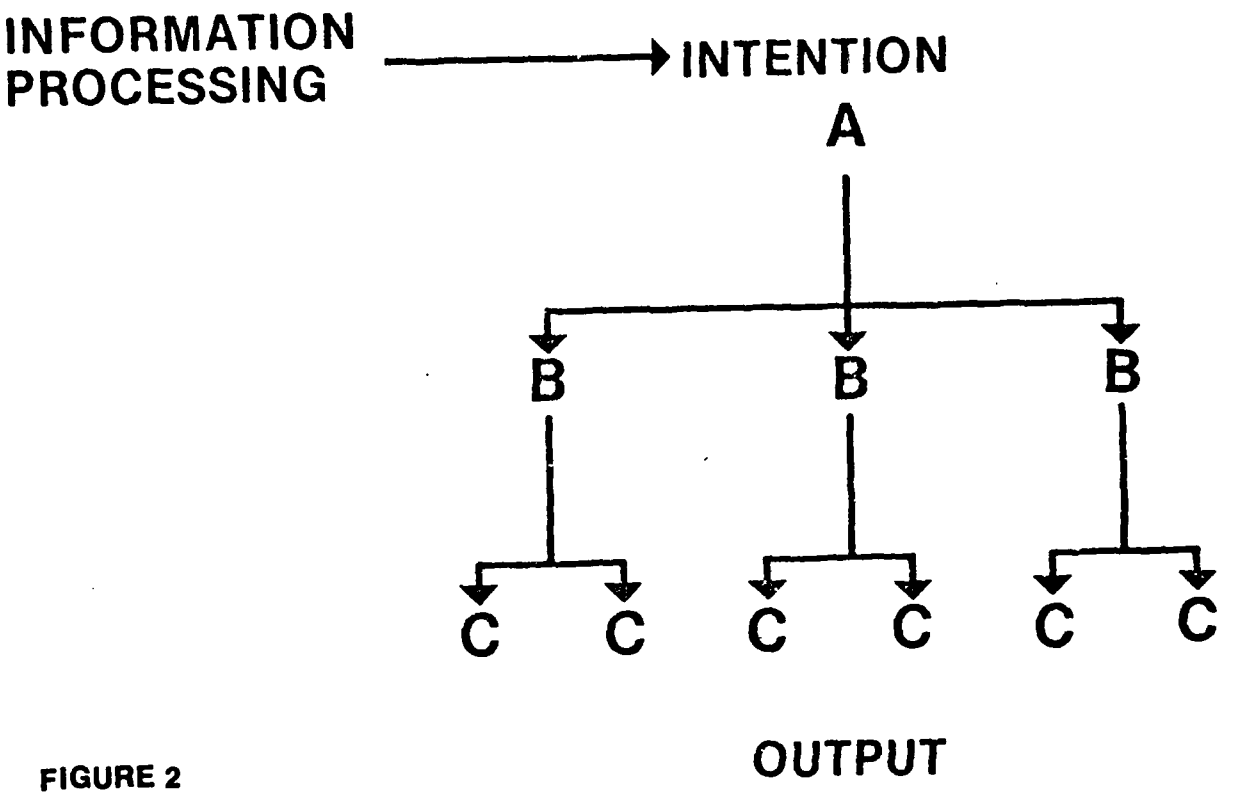



FIGURE 2

## HIERARCHICAL, MULTI-LEVEL, DISTRIBUTED CONTROL

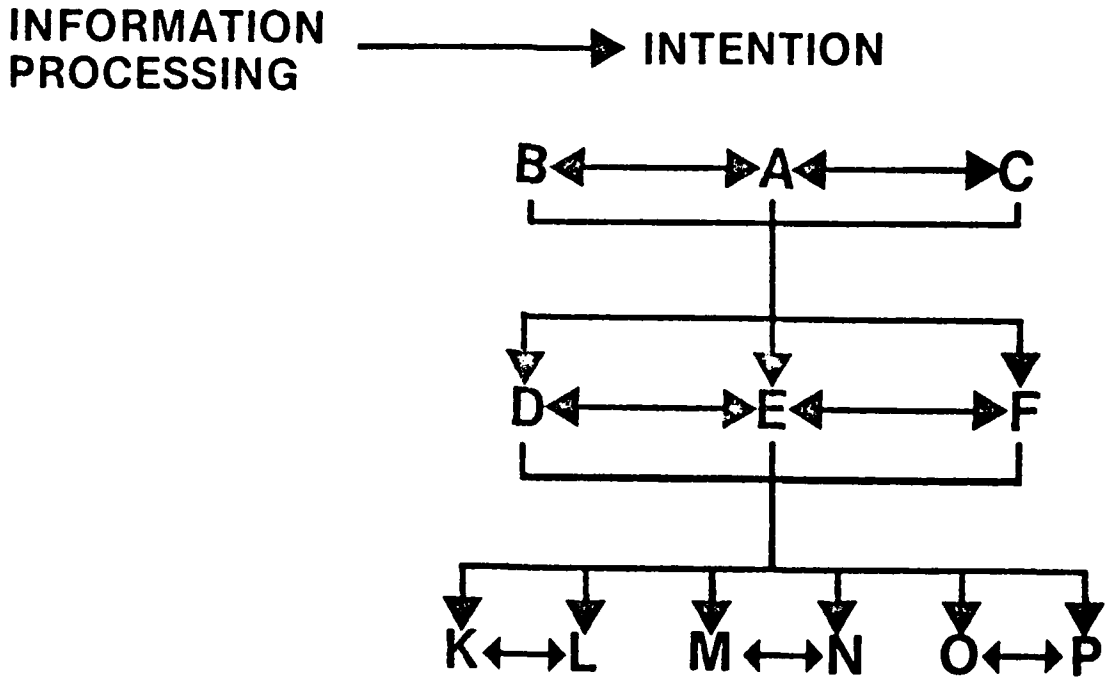
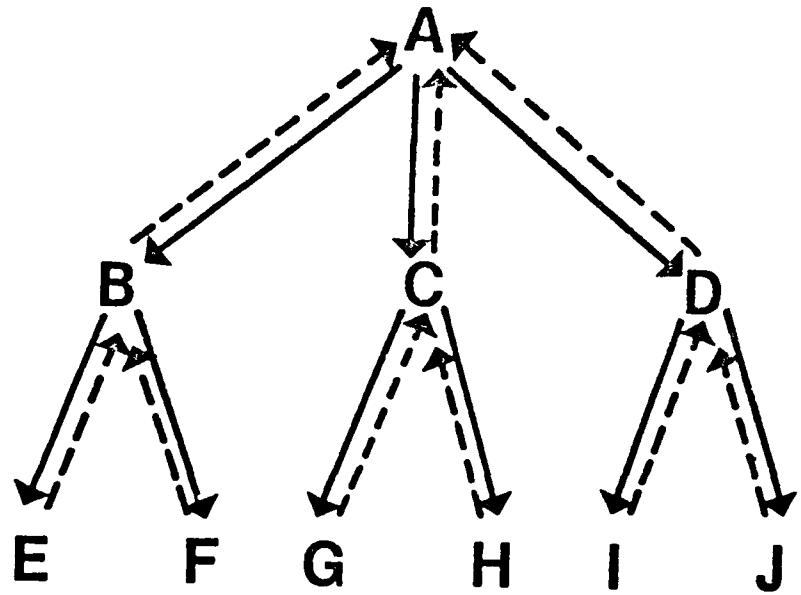



FIGURE 3

# HETERARCHICAL CONTROL

INFORMATION PROCESSING → INTENTION




OUTPUT

FIGURE 4

# Part II

# On the Relationship Between Response Organization Processes and Response Programming

George E. Stelmach
Douglas D. Larish

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## ABSTRACT

Urgent practical and theoretical concerns about humans' processing of and responses to machine-generated information provide the rationale for this research. Clearly, maximizing the user's efficiency in processing information is of high priority in all practical fields, although it seems especially so in a military context. This research employs an information processing approach in order to better define the operator's motor response programming characteristics in relation to other nonmotoric processes. By utilizing both movement precuing and additive factor techniques, manipulations in pre-movement knowledge of the upcoming action's direction and extent can reveal (via reaction times) a good deal about the order in which these two parameters are programmed and the extent to which their programming can be considered serial (one being accomplished prior to the other) or parallel (with temporal overlap). Further, levels of precued information are combined with translational manipulations in order to particularly address an issue critical in motor programming: whether a nonmotoric decision, stimulus-response translation, can be identified as a confounding element of earlier conceptualizations of motor program construction.

In order to resolve this issue it was deemed necessary to show that 1) stimulus-response translations are localized in a response determination stage (Theios, 1975) rather than the response selection stage and 2) when a translation is required earlier results (Rosenbaum, in press) would be supported, but when a translation was unnecessary a different pattern of results would emerge. In Experiment 1, inspection of the data revealed that the main experimental variables were differentially affected by practice,

and it was concluded that the obtained results failed to accurately reflect the true relationships of these variables. Experiment 2 eliminated this differential practice effect and the outcome of both reaction time and determination time data analysis supported the independence of the response determination stage.

The fact that the differential programming effect was found only when a translation was required, and that it was localized in determination time rather than selection time, was seen as a definite indication that earlier accounts of motor programming had inadvertently, but ominously, included in the response programming stage a nonmotor process. Further discussions focused on the internal operating characteristics of response determination and response selection, along with their possible interactive relationships.

# INTRODUCTION

Increasingly, advances in computer and other electronic technologies are changing the relationship of the operator and the machine. Rather than remaining a simple controller of the machine, an operator's roles now involve the monitoring, processing, decision making and responding to machine-generated information. The import of an understanding of the means by which the operator utilizes and responds to such information is obvious. More rapid and more accurate performance is desirable in practically every situation in which the operator and machine interact. In many instances, in fact, and particularly in the military, the operator's efficiency in processing information and responding may be of life-saving utility. The judicious selection of suitable personnel and the training of them for tasks requiring rapid and accurate response to electronic information can only be aided by improved cognizance of the exact processes being undertaken by the operator. Furthermore, and of clear relevance in experimentation such as this, improved knowledge of the operator's processing characteristics can and should lead to the development of more appropriate informational instruments.

At a more specific level, this research is important for a number of reasons. It is now uncontestably held that complex motor sequences can be effected in the absence of peripheral feedback (Kelso, 1977; Sperry; 1969; Taub & Berman, 1968;Teuber, 1974). This position contends that motor acts are controlled by a central, rather than peripheral source, and for the purposes of the present investigation the mechanism of control will be called a motor program (MP). An alternative to deafferentation studies (where peripheral information is either permanently or temporarily

removed) in the indexing of central processing and motoric preparation has been to use reaction time. Assuming that a MP is programmed before movement begins, the time to prepare it should reflect the complexity of the upcoming act (Henry & Rogers, 1960). The development of the research examining motor programming no longer focuses solely on verifying the existence of MP's, instead it is more concerned with illuminating the composition, structure, and operating characteristics of the MP. In other words, it is felt researchers should begin to try to better understand the elements that make up the MP. As a result, the current research emphasis focuses on the planning and organization processes that precede movement initiation, and such a framework has been aptly termed response programming. Furthermore, from a human information processing (HIP) point of view these planning activities are said to occur within a processing stage termed response selection (Kerr, 1978). Although programming is usually thought to be confined to the response selection stage, the contention here is that a number of published studies have actually confounded response selection with a second processing stage: response determination (Teichner & Krebs, 1974; Theios, 1975). Within the HIP framework, and relying upon the additive factors method (Sternberg, 1969; Taylor, 1976), two experiments were conducted to provide empirical support for such an assertion.

## REVIEW OF LITERATURE

It is well known that the voluntary initiation of motor action involves efferent discharges from the motor cortex to spinal motoneurons and muscles (Eccles, 1977). Open loop theorists have maintained that these efferent commands convey specific information about which muscles contract, along with the order, force, and duration of contraction. In other words, this central innervation contains all the specifications for coordinated action. Throughout the 20th century the mechanism for open loop control has been referred to as a victorola record (Hunter, 1930), a score (Weiss, 1950), a memory drum (Henry & Rogers, 1960), and a motor program (Keele, 1968). The motor program concept has been the most enduring, and has been defined as a set of muscle commands, structured before a movement begins, that allows the entire sequence to be carried out uninfluenced by peripheral feedback (Keele, 1968). Although such a definition has been recently criticized as being too restrictive in its account of motor control and coordination (Easton, 1978; Fitch & Turvey, 1978; Kugler, Kelso & Turvey, 1980; Schmidt, 1975), it is nevertheless a useful one for the present purposes. This definition implies that a preparation or planning process is an important precursor to overt action, and accounts, in part, for why the operational characteristics of the planning process have become a prominent

research concern.

Although the behavioral study of the structure of the MP has taken on many forms, a common format for these investigations is the use of both rapid ballistic motor acts and as the principle dependent measure reaction time (RT). Ballistic movements are deemed most appropriate because programmed control must be studied under conditions where sensory feedback can be ruled out as a regulator of performance. Since feedback processing delays are well documented (Chernikoff & Taylor, 1952; Henry & Harrison, 1961; Keele & Posner, 1968; Pew, 1966), it is argued that rapid movements must be pre-planned and under MP control. RT is a popular dependent measure because it is thought to directly reflect the organizational structure underlying response programming. The basic experimental attack has been to vary the nature of the response to be made and observe how this influences the length of the RT delay. The observed relationships between RT and response parameters are then used to deduce the properties of the programming process, and ultimately the MP itself.

## Structure and Contents of Motor Programs

Two problems are basic to an understanding of the control of complex, temporally structured motor acts. The first problem concerns the serial order (sequencing) of actions and the second problem concerns the timing or temporal constraints under which the sequencing of action proceeds. Since both sequencing and timing have been

recognized as necessary components of the MP (Huggins, 1978; Keele, 1975; Keele & Summers, 1976; Lashley, 1951; Summers, 1975, 1977; Vorberg & Hambuch, 1978; Wing, 1973), the following discussion focuses on their individual and interactive roles in the programming of motor actions.

Sequencing of action. How is the sequencing of successive motor responses accomplished? How are these responses linked in the memorial structure of the MP? Keele (1975) reasoned that the sequencing of action in the MP was based on either event-to-event associations or event-to-position associations. The former instance simply means that successive responses are associated with each other, such that the termination of one response is the signal for the next one to begin (similar to James' response chaining hypothesis). The latter instance, on the other hand, maintains that associations are independent of any contiguity among responses, but are instead derived on the basis of an event's particular position in the response sequence.

To contrast these two positions, Keele (1975) selected a keyboard task in which the eight fingers were paired with eight stimulus lights. The basic task was to depress a RT key under the finger when its corresponding light was illuminated. In an initial training phase, subjects practiced an invariant response sequence (e.g. 1 8 3 4 7 5 6 2) until they could respond rapidly and accurately. In the subsequent experimental phase, one response light deviated from the learned pattern; it was cued out of sequence. The issue was how well

one could respond to the first event back in sequence, and this first response back in sequence had either an event or position relationship with the out of sequence response. More specifically, if successive responses are based on a position association, response time to the first event back in sequence should be faster when this response is the normally occurring event in that position of the sequence. For example, given the previous sequence, inserting 6 after 4 constitutes an out of sequence event. The test for position associations would have 5 as the first event back in the sequence, since it would be occurring in its learned position. Alternatively, if the memory structure is based on event associations, response time should be faster when the first response back in sequence is the one that always follows the out of order event. Returning to our example, 2 would be the first back in sequence event since it always follows 6.

One additional variable included in the experiment was the interval between a response and the subsequent stimulus light: The response-stimulus interval (RSI) was either 50 msec or 1500 msec. Keele (1975) reasoned that the shorter RSI might better discriminate between the two alternatives because the optimal association should prevail when time constraints were imposed, whereas, the longer RSI might allow both types of associations to be used effectively.

The results of this experiment revealed that event associations were more effective in reducing RT to the first back in sequence response when the 50 msec RSI was involved. No differences, however,

were apparent for the longer 1500 msec RSI. Keele (1975) interpreted these findings to mean that the basic memory structure for motor program representation consisted of event-to-event associations.

Such a conclusion seems to be reasonable when the only relationship among responses is one of linear position. Yet, one can inquire whether such associations would dominate if the successive responses are given an underlying structure. This latter inquiry is perhaps more interesting since it concerns the issue of higher order cognitive categories and their role in the memorial representation of the MP.

Restle and Burnside (1972) reported a series of experiments that do indeed suggest that a binding organizational format affects the particular memorial structure adopted. Using an experimental task similar to Keele (1975), but using six possible responses instead of eight, subjects were required to execute button presses coincident with light onset. Subjects were required to predict the onset of the "go" signal so that their response and the signal were simultaneous. A further difference was the arrangement of finger responses in the sequence to be executed. Each sequence contained 16 individual events and these events were linked according to one of four subpatterns. These patterns were either 1) runs (e.g. 1234), 2) reverse runs (4321), 3) repititions (2222), or trills (1212).

Restle and Burnside (1972) were not interested in RT, but rather response errors. Specifically, they wanted to know if errors would be more frequent at transition points in the sequence. These

transition points were defined as a change from one organizational pattern to another. For example, the last response in a run and the first response in a trill would qualify as a transition point. One pattern of 16 responses used was 1 2 3 4 6 6 6 6 6 2 3 2 3 5 4 3. The data showed that higher than average error rates occurred at the last 6 in the repitition, with 2 being the most common error; and the end of the run, with the insertion of a 5 being the most common error. These results clearly demonstrated that the frequency of errors was directly related to the junction points between sub-patterns in that errors tended to occur at the beginning and the end of a pattern. Thus, it appeared as if subjects were using a cognitive rule to mediate performance and each pattern had its own rule. It should be pointed out that such rules support an event-to-position interpretation and agree with Lashley's (1951) assertion that the structural pattern underlying a series of responses influences performance to a greater degree than event associations.

Considering the Keele (1975) and the Restle and Burnside (1972) data together two conclusions about the memory structure of the MP can be made. First, the MP representation for unpatterned sequences consists of event-to-event associations. Second, when higher order rules underlie these successive responses they appear to dominate and override the contiguity of sequential associations.

Rabbitt (1966), Rabbitt and Vyas (1970), and Rabbitt, Vyas, and Fearnley (1975) also investigated the response programming of serial

events, but their research efforts had a somewhat different focus. They were interested in how the programming characteristics of contigous responses influenced each other. Variables manipulated in these studies included the programming of intra- and inter-limb responses, repitition and alteration responses, and the complexity of successive responses.

Rabbitt (1966) required subjects to react to four different signals by movements of the hands and feet; one signal was paired to each limb. The experimental manipulations were repitition versus alteration responses crossed with intra- and inter-limb programming. Rabbitt reported that RT's of repeated responses within the same limb were faster than RT's of alternating responses between limbs. More interesting results, however, were obtained when only inter-limb combinations were examined. Contra-lateral responses of the same kind (e.g. right hand followed left hand) were faster than contra-lateral responses of a different kind (e.g. right hand follows left leg). Finally, the slowest and most error prone transitions were responses made by ipsilateral limbs of a different kind (e.g. left foot follows left hand). From these results, it was concluded that serial programming time was dependent upon both the type of limbs and the laterality of limbs involved.

In a later study, Rabbitt and Vyas (1970) examined these generalizations when the selection of appropriate responses was just among the fingers of both hands. Unlike the ipsilateral transitions

in the earlier study, a response made with any finger was faster when it followed a response by a different finger on the same hand, than if it followed a response by another finger on the opposite hand. In this instance, ipsilateral transitions appeared to be facilitating. The combination of responses that resulted in the fastest RT's also differed from the previously reported data. Here the fastest responses occurred when a response made with one finger on one hand followed another response made with the symmetrical finger on the opposite hand (e.g. right middle finger followed the left middle finger).

Rabbitt, Vyas, and Fearnley (1975) subsequently investigated how manual finger responses were organized into coordinated sequences of action. Rabbitt et al. reasoned that individual responses would be cumbersome to program and thought a more reasonable alternative was that a series of movements were programmed as a group. The question of interest, therefore, was whether the inclusion of the same response component in successive movements would lead to greater ease in programming. In an initial experiment three responses were possible; left fore-finger, right fore-finger, and both together. In the latter instance, both finger responses were made simultaneously, and any situation that involved more than one finger in an independent response was called a chord. Subjects experienced eight series of 150 responses and the RSI interval was 200 msec. The RT data was separated according to the six possible categories of transitions

between responses. Analysis of the results revealed a complexity effect in that single finger responses were faster than the two finger chord responses. Further analyses showed that one finger repititions were faster than one finger alterations, one finger alterations were faster than cases in which one finger responses followed two finger chords, and chord repititions were faster than if they followed one finger responses. Such results clearly pointed out that a common component in successive responses actually inhibited RT. Consequently, Rabbitt et al. (1975) concluded that overall response organization, and not the inclusion or exclusion of certain sub-patterns, was responsible for the present data. The important property that seemed to create these findings in this serial programming task was response complexity.

To evaluate this assumption in more detail a subsequent experiment manipulated complexity by increasing the size of the finger chords. Four different fingers were used (the fore and second finger on each hand), resulting in 15 possible responses: there were four possible one finger responses, six possible two finger chords, four possible three finger chords, and one possible four finger chord. The main effect of complexity revealed the anticipated RT increase as a function of the number of responses, except for the four chord combination. In this instance, RT approximated two chord combinations. The data were also analyzed with respect to the complexity between transitions. RT's for responses of differing complexity were

examined on the basis of the preceding response's complexity. In general, this analysis revealed that the more complex a response, the more sensitive it was to the complexity of the prior response; thereby substantiating the earlier experiment. Furthermore, the complexity of transitions seemed to be defined by the complexity of choices between the two hands. Other comparisons indicated that successive different responses within a hand were faster than different responses between hands. It was also easier to respond with one hand after having just used the other, than to respond with one hand after having just used both together. Finally, responding with both hands was more rapid if the preceding response involved a different movement using both hands, than if the prior movement involved only one hand.

In general, Rabbitt and his associates have demonstrated that response complexity has a systematic effect on the structure of sequential responses. Thus, any account of serial patterning must account for the nature of the successive choices between hands, the nature of the choices between fingers, and the number of fingers used in contiguous chords.

Temporal regulation of action. In addition to sequencing, a second component of motor program structure necessary for movement execution is timing. Motor actions not only require parameterization of sequential components, but these components must also be initialized within some time frame.

A series of experiments reported by Restle (1972) demonstrated rather convincingly the important role that temporal organization commands in response programming. The basic characteristics of Restle's (1972) experiments were similar to those described earlier (see Restle & Burnside, 1972). A keyboard task was used in which six finger movements were possible. Subjects were required to learn and execute 20 different response sequences, each containing 16 responses. All sequences were composed of the four sub-patterns previously defined; run, reverse run, trill, and repitition. The temporal structure of a serial pattern was manipulated by varying the RSI between successive responses.

Each sequence was constructed such that major and minor transitions (as defined by Restle) could be identified. The primary experimental variation (termed phrasing) concerned the RSI length at these different sub-divisions. "Good" phrasing was defined as the placement of relatively long pauses (RSI's) between super-ordinate divisions in the sequence and shorter pauses between sub-ordinate divisions. Conversely, "bad" phrasing was defined as the placement of relatively short intervals at the super-ordinate junctures and longer intervals at sub-ordinate junctures. As an example, consider the following sequence: 1 2 1 2 2 3 2 3 6 5 6 5 5 4 5 4. According to Restle, the most important division separates the sequence in half (e.g. between the 3 and 6). Each half in turn contains several less important divisions which are alterations (1212 and 6565),

runs (12) and, reverse runs (32, 65, and 54).

Restle and Brown (1970 a,b) had previously reported that errors in serial patterning most often occurred at the prominent divisions in the sequence. Furthermore, "good" phrasing resulted in more accurate performance. Restle (1972) was interested in a more in-depth explanation and offered two plausible hypotheses. First, phrasing may function as a parenthesis, identifying the boundaries among relevant sub-patterns that can be subsequently used to organize the sequence structure. Second, the major divisions occur at junctures in the sequence where uncertainty and information load is high, so that the extended pauses might allow more time for information processing. In the former, the relative spacing between responses would be most important, and in the latter, absolute time would be most important.

In Experiment 1, the intervals between "go" signals were phrased well, not at all, or badly, and were either short (averaging 300 msec) or long (averaging 800 msec). Borrowing from musical definitions, the short intervals had an allegro rhythm and the long intervals had an adagio rhythm. Therefore, good phrasing at an allegro rate gave subjects 600 msec or 400 msec at critical junctures and 200 msec or 300 msec at all others, whereas, adagio presentation with no phrasing gave subjects 800 msec at all divisions. These were the principal conditions testing the experimental hypothesis. Even though the allegro rate gave less time at each junction, it resulted in better

performance than the adagio rate. On this basis, Restle (1972) concluded that good phrasing provided a temporal parenthesis which identifies the various sub-units within the serial pattern, and thereby facilitates performance.

A subsequent experiment examined the effect of presentation rate further by replacing the adagio rate with a presto tempo rate, which is much faster than either allegro or adagio. In addition, the previous experiment gave some indication that bad phrasing had a detrimental effect on performance, and this issue was also pursued by dividing the serial pattern into segments that conflicted with the inherent structure of the sequence. For the most part, Experiments 1 and 2 yielded similar results and conclusions. Compared to a no phrasing condition, both the presto and allegro rates facilitated performance and partitioning the sequence into inappropriate groupings proved to be quite detrimental. Collectively, then, these data strongly suggest that phrasing and rhythm (timing) are important determinants in the performance of motor tasks. In fact, temporal structure has been shown to be a critical and necessary component in motor skills ranging from the playing of musical instruments (Shaffer, 1980) to the intelligibility of speech (Huggins, 1978; Klatt, 1975). For example, the poor intelligibility in the speech of deaf individuals has been attributed, at least in part, to inappropriate phrasing (pauses often too long or too short) and lack of contrast between the durations of stressed and unstressed syllables (Huggins, 1978).

Although the present discussion argues for the importance of timing in response programming, a question left unanswered concerns the exact relationship between serial order and temporal structure. More specifically, are the sequencing of action and the timing of action separate, independently programmable features of the MP? During the response programming process are serial ordering and timing performed by mutually exclusive mechanisms? Is timing an integral part of the MP representation?

Preliminary support for the coupling of these two factors came from Glencross (1973), who observed that hand cranking at a variety of overall speeds failed to alter the relative timing of different movement components. This study is only suggestive, however, since subjects were not required to change the timing pattern of the component movements. A more convincing argument would have been possible had subjects been instructed to do so, and it was found that they were unable to perform effectively under the new temporal constraints.

Recognizing such a limitation, Summers (1975) required subjects to learn one constant sequence of 10 finger responses in which the RSI between successive movements followed a specified pattern. Two such repeating rhythmic patterns were used: 1) 500-100-500 msec and 2) 100-100-500 msec. Control conditions included a constant 300 msec RSI and one with randomly chosen RSI's (100, 300, or 500 msec). After a training phase where visual signals cued each response, two experimental phases were introduced. First, subjects were required to

repeat the sequence from memory, keeping the same RSI pattern learned in the training phase. During this period, the rhythmic groups demonstrated that they were able to maintain the general temporal structure rather accurately. Second, subjects were instructed to disregard the learned temporal structure and execute the entire response sequence as quickly as possible. This latter phase was the experimental test of whether timing was an inherent part of the MP since a previously learned serial pattern had to be performed using a new underlying pattern. All four groups were able to increase the overall speed of responding (the entire sequence was completed in less time), but the 5-1-1 group and the 5-5-1 group still showed the influence of the previous timing constraints. Summers (1975) concluded that overall movement speed may be an independently programmable parameter, but that the relative timing of events within a sequence was an inseparable characteristic of MP representation, especially in skills involving rhythmic timing structures.

In a follow up study, Summers (1977) introduced out of sequence events similar to the technique used by Restle and Burnside (1972). Two groups were included in this experiment. A timing group, which had a constant 300 msec RSI, and a no timing control group, which received randomly chosen RSI's (100, 300, or 500 msec). Summers hypothesized that if the MP itself contains no information about temporal structure, error rates to the out-of-order events in both groups should be equivalent. Analysis of the data, however, revealed just the opposite

pattern. Errors to the unexpected changes in event order were larger in the timing group, providing further support for integration of timing and serial order into MP structure and representation.

Wing (1973) has also reported data, using a morse key tapping task, that he interpreted as evidence for the coupling between serial order and temporal organization. In addition, Huggins (1978) presented similar findings for the syllable duration of spoken words. Huggins noted that a change in syllable duration influenced all segments in the syllable, either all segments were lengthened or all shortened, but no change in the relative timing relationships between segments ocurred.

In concluding this section, it is readily apparent that the empirical evidence suggests that the functional integrity of two parameters in MP representation must be recognized. Although serial order is most likely the basis of motor responding, it is sensitive to the influence of higher order, cognitive organizational rules, of which timing is one. When invoked, both serial order rules or temporal rules have a very powerful and positive effect on sequencing performance.

## Movement Parameters Affecting Response Programming

Thus far, the discussion of response programming has been confined to situations where sequences of responses had to be executed. A single discrete response framework has also been used to examine the basic characteristics of the programming process. In a typical experiment, variables that are thought to affect the length of the planning and organization process prior to movement initiation are manipulated.

Two basic experimental paradigms have been extensively used within the discrete response framework; simple reaction time (SRT) and choice reaction time (CRT). In a SRT situation subjects have full knowledge of the intended response prior to movement initiation, and the task is simply to execute the designated act on the occurrence of a "go" signal. In the SRT procedure no uncertainty about the intended movement exists, and it is therefore assumed that the response can be programmed prior to a "go" signal. Klapp (1978) and Rosenbaum (in press) have criticized the use of the SRT task because it is unable to provide information about the actual construction of the MP and as an alternative both advocate the use of a CRT procedure. Since response uncertainty involves the choice among a number of response alternatives, the characteristics of response programming can be examined by varying the movement parameters that are unknown before the "go" signal is given. Initiation time, then, is thought to reflect the programming time of the unknown variable(s). A more detailed treatment of this debate can be found in Klapp (1978) and Sternberg, Monsell, Knoll, and Wright (1978). For ease of presentation the response programming studies to be discussed in this section are divided into these two general categories and emphasis is placed on identifying the movement parameters thought to influence the programming process.

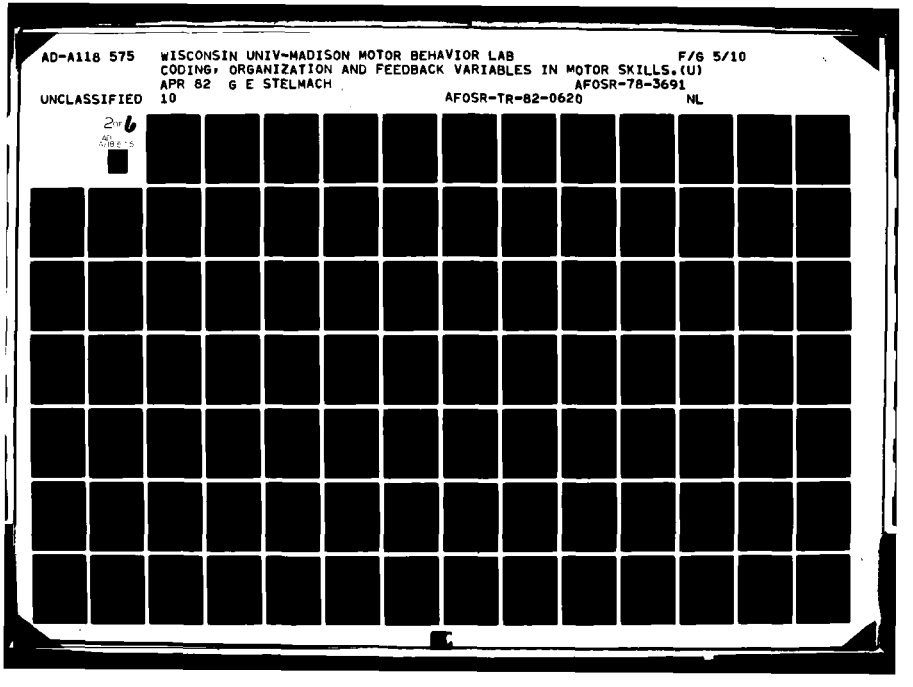
Simple reaction time. The use of SRT to assess the planning stages of response initiation seems to have originated with Henry and

Rogers' (1960) work on the relationship between reaction time (RT) and movement complexity. Movement initiation time was contrasted for three different movements: Movement A just required a finger release from a response key; Movement B involved releasing the key and grasping a tennis ball; Movement C involved releasing the key, knocking down a tennis ball, reversing direction, pressing a dummy push button, and reversing direction a second time to knock down another tennis ball. The first task was easiest, the second harder, and the third hardest. The results of this experiment revealed that initiation time increased as a function of complexity and it led Henry to develop his Memory Drum Theory of neuromotor reaction. Simply stated, during the preparation phase of a movement the motor commands governing execution are assembled and stored in a response output buffer or memory. Movement initiation occurs after the program has been released from the buffer and the appropriate muscles have received the motor commands. Henry (1961) maintained that the more complex a response sequence the larger the program had to be and the more time needed for it to be read out of the buffer. In a SRT task it is this readout time that is indexed by response latency.

Norrie (1967 a,b) conducted very similar experiments, where she too reported an increase in RT as the task requirements of a reaching movement became more complex. In a study by Glencross (1972; Expt. 2) the complexity of movement was increased by inserting two or three tapping movements in a lateral arm sweep. When compared to initiation

time for a simple key release and arm sweep alone, these more complex movements did indeed have longer RT's. Virtually identical results have also been reported in speech production and typewriting. Monsell and Sternberg (Note 1) and Sternberg, Monsell, Knoll, and Wright (1978) showed that SRT was a linear function of the number of items to be pronounced and the number of words to be typed.

The precision requirement of movement has also been considered as a movement parameter that might influence response complexity: Movements requiring a greater degree of terminal accuracy are more complex. Unfortunately, the evidence for the utility of this parameter is equivocal. In an initial experiment, Glencross (1976) contrasted three movements; lateral arm sweep (no accuracy requirement), aiming movement to a large target, and aiming movement to a small target, and found no differences in SRT among the three movements. In two subsequent experiments, however, a complexity effect was found when the lateral arm sweep was made to targets of 1.2, 2.5, and 5.1 cm in width. Unfortunately, these findings are not very meaningful because these differences in RT were accompanied by increased error rates and movement times (MT). Thus, complexity was confounded with the speed-accuracy trade-off phenomena (Pachella, 1974). In a discrete tracking task, Laszlo and Livesy (1977) reported an effect of movement precision. Subjects were required to move a stylus across a moving paper strip so that they contacted either zero, one, or two dots placed at irregular distances. The results revealed that initiation


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time for the zero or no-dot control condition was significantly lower than for the one and two-dot conditions, which failed to differ from each other. Other null result experiments, however, were those of Kerr (Note 2, Note 3), in which she was unable to find variations in RT resulting from decreased target width.

Glencross and Gould (1979) contended that these inconsistent findings resulted because RT as a latency measure does not reliably reflect the complexity of the planning process. Since the uncertainty about programming is alleviated in a SRT task, initiation time simply reflects output time of the program from a response output buffer. Therefore, all the movement planning has occurred prior to RT. As an alternative, Glencross and Gould (1979) suggest the RT probe technique since it would allow one to measure the attention demands during the programming period (usually between a warning signal and "go" signal). Presumably more complex movements would require greater attention demands, and hence, higher probe RT's. Using essentially the same movement paradigm as Glencross (1976), Glencross and Gould conducted two experiments with the inclusion of the probe methodology. In both experiments, the complexity effect for precision was found in probe RT, but not in RT. These preliminary data would appear to support the assertion made above and certainly offers a viable alternative to the use of only RT.

Another movement parameter that has been questioned as an indicant of complexity is movement extent. Brown and Slater-Hammel (1949) were

the first to report that initiation time was independent of movement lengths ranging from 2.5 to 40 cm. Lagasse and Hayes (1973) found the same result when they contrasted elbow flexion for a simple key release and for a 140 degree movement. Glencross (1976; Expt. 3) also failed to find differences in initiation time between movement extents of 15.24 and 30.48 cm. In a tracking type task, Semjen, Requin, and Fiori (1978) reported that initiation time was unaffected by movement extent. On the basis of the above data it appears that movement length is not a factor influencing programming time, at least not in SRT tasks.

Other movement parameters that do not appear to increase movement complexity, at least in a SRT, are force (Glencross, 1973) and direction (Glencross, 1973; Semjen, Requin & Fiori, 1978). One final movement parameter to be considered is the number of limbs involved in a response. Glencross (1973; Expt. 5) compared initiation time for a one arm movement and a simultaneous two arm movement under two movement conditions; lateral arm sweep and lateral arm sweep with a reversal movement. Analysis of the data indicated that in both instances the simultaneous situation created significantly larger initiation times. Kelso, Southard, and Goodman (1979) have since replicated this finding.

In summary, of the movement parameters discussed, only complexity, as defined by increasing the number of movement segments or limbs, has had a consistent influence on RT. For terminal accuracy, the data were

equivocal; and for force, direction, and extent, no positive results have been reported in the literature.

Choice reaction time experiments. Unlike the SRT procedure, in a CRT task the desired movement is unknown prior to the response signal. Thus, uncertainty about the exact movement is present and only when the "go" signal has been given can this uncertainty be alleviated. Within the present framework, uncertainty reduction is the programming of the unknown response parameters. As a result, CRT is measuring more than just the output time of a MP from a response output buffer (see Henry & Rogers, 1960; Sternberg, Monsell, Knoll & Wright, 1978). By varying the unknown parameters, one can infer (from RT) how these parameters influence and fit into the programming and construction of the MP.

Klapp and his colleagues (Klapp, Wyatt, and Lingo, 1974; Klapp & Wyatt, 1976; Klapp & Erwin, 1976; Klapp, 1975, 1977) presented a series of studies that suggested movement timing was an important parameter included in the response programming process. In both a SRT and CRT situation, Klapp, Wyatt, and Lingo (1974) had subjects perform two movements differing in their timing components. The programming of timing was manipulated by having subjects execute either a morse code "dit" or "dah" response. The "dit" involved depressing and immediately releasing the response key (release movement), whereas, the "dah" involved depressing the key, momentarily holding, and then releasing the response key (hold movement). Klapp et al. (1974)

argued that a "dah" response was more complex because of the timing delay introduced by the hold component. The results of two experiments showed that initiation time in the SRT condition was equivalent for both movements. In contrast, for CRT the results revealed that "dah's" took longer to initiate than "dit's". As an aside, the different pattern of results between the SRT and CRT situation is the primary reason why Klapp (1978) advocates the use of CRT as the most appropriate measure of programming time. Klapp and Wyatt (1976) and Klapp and Erwin (1976) also reported similar results, suggesting that response timing or duration is programmed prior to movement initiation.

In a further study Klapp (1977) inquired whether the muscles of execution had to be known before other aspects of the movement (e.g. timing) could be programmed. Klapp covaried the dit-dah response manipulation with the finger and thumb. Initiation times for the dit and dah movements were contrasted under two conditions; timing-uncertain and muscle-uncertain. For the muscle-uncertain instance, subjects knew the timing component but not the muscles to be used. Analysis of the data revealed that when the muscle dimension was uncertain (or timing known), RT for the dit and dah responses was equivalent. In the timing uncertain condition (or muscles known) the results were quite different. The usual latency effect was found; dah RT's were longer than dit RT's. Klapp took these results to indicate that the timing requirements could be established and programmed even if the muscles for execution remained unspecified. In other words, there is no

specific order in which these two movement parameters must be compiled.

Programming time for the spatial dimensions of direction and extent have also been studied. Megaw (1972, 1974) and Megaw and Armstrong (1974) reported a series of experiments in which direction and extent uncertainty were manipulated. Prior to response initiation, subjects knew the direction of movement (right or left), but not the extent (extent-uncertain); knew the extent (near or far) of movement, but not the direction (direction-uncertain); or knew nothing about the movement characteristics of the intended movement. Megaw found that RT's for the direction-uncertain condition were longer than RT's for the extent-uncertain condition. Further, when both direction and extent remained to be programmed, initiation time was equivalent to the direction-uncertain condition. From these data Megaw inferred that direction was specified before initiation, whereas, movement extent involved an updating process after the movement had begun.

Kerr (1976) has pointed out, however, that Megaw's (1972) results may have been created by the experimental task used. Subjects had to align a pointer in correspondence with a designated movement light. The peculiar aspect of the task was that to move the pointer in the right direction subjects had to move their arms in the left direction. Consequently, there was a certain degree of incompatibility in the direction dimension that Megaw failed to recognize. When extent was uncertain this posed no problem since subjects could determine the appropriate direction of movement before the "go" signal. That is, the

incompatibility due to direction could be overcome prior to the onset of the stimulus cue. The same argument can not be made in the direction-uncertain condition. In this instance, initiation time is an index of two factors; overcoming the incompatibility and programming direction. It should be added that plenty of evidence exists demonstrating increases in RT when a stimulus and response are incompatible (Fitts & Seeger, 1953; Teichner & Krebs, 1974). Therefore, Megaw's RT's for direction programming are confounded with stimulus-response incompatibility. Unfortunately, the data presented by Kerr (1976) fail to clear up this issue because error rates and movement times in conditions to be compared were unequal. Such a result makes the data spurious because subjects were not performing consistently across different experimental conditions. Therefore, subjects likely traded-off between speed and accuracy (Pachella, 1974).

Other studies manipulating only the direction and extent parameters have been consistent with regard to the RT effect of both direction and extent uncertainty. Semjen et al. (1978) and Kerr (Note 2, Note 3) reported that direction and extent decisions increased the RT delay. Such results imply that each parameter was programmed prior to movement initiation.

Does movement accuracy or precision influence the length of the RT interval? According to Klapp (1975), CRT increased as the accuracy requirement in a target aiming task became more difficult. In a Fitts tapping task and for relatively short movement lengths (2 and 4 mm), RT

depended on target diameter, with longer times for smaller targets (2 and 4 mm). Klapp concluded that more precise movements required longer programming time. Kerr (Note 2, Note 3), on the other hand, was unable to demonstrate any increases in programming time resulting from increased precision. In three experiments, and across four target diameters (1.8, 2.7, 3.6, and 4.5 mm), RT was invariant as a function of size. In opposition to Klapp, Kerr concluded that movement accuracy was not a particularly important factor entering into the programming process. Recall that in the discussion of SRT experiments, the findings concerning accuracy were also spurious. Taken as a whole, one must question whether this task manipulation can be viewed as an important and functional component of response programming.

Programming time has also been examined by varying the complexity of the response components in movement execution. Early studies by Glencross (1972, 1973) were unsuccessful at increasing RT via complexity, however, more recent studies by Kelso, Southard, and Goodman (1979), Klapp and Erwin (1976), and Rabbitt et al. (1975) have shown that movement complexity does indeed influence programming time. In comparing single limb and simultaneous double limb movements, Kelso et al. demonstrated that the simultaneous condition had longer RT's. Results from Rabbitt et al. indicated that RT's became longer as the number of fingers in a chord increased (refer to section on serial patterning). Klapp and Wyatt (1976), using dit-dah (release-hold)

movements, found that the RSI between two successive responses was longer when the first was a hold movement as opposed to a release movement. Not only does such a finding agree with that of Rabbitt et al. (1975) as discussed in an earlier section, but it also supports the contention that movement complexity affects response programming.

To sum up the CRT data thus far, it appears that the duration or timing parameter is a critical component in the programming of simple movements. The consistency of Klapp's and his colleagues' data forces one to such a conclusion. Furthermore, this conclusion agrees nicely with those made about the relationship between temporal structure and serial patterning. Direction and movement complexity also seem to be parameters that must be initialized and accounted for before a movement can begin. Such a statement about movement extent and movement precision, however, is more difficult to accept. The studies concerning these latter two parameters are either equivocal or suffer from methodological anomalies.

Movement Precuing Technique

More recently, Rosenbaum (in press) has extended the long-standing Partial Advance Information (PAI) paradigm (Leonard, 1958) to examine the operational characteristics of MP construction; this variation is termed the precuing technique. In a typical precuing experiment, subjects are required to execute simple limb movements that vary on a number of movement dimensions (e.g. arm, direction, extent, duration). Prior to a reaction stimulus, advance information

(precue) is provided about the characteristics of the forthcoming movement. The precues can signal either total, partial, or no knowledge about the intended movement, and herein lies the utility of this technique. By including all possible combinations of precues one can gain insight into the independent and interactive roles each of the movement parameters has in MP construction.

Rosenbaum (in press) manipulated three movement parameters and these included arm (right or left), direction (forward or backward), and extent (near or far). Thus, eight distinct movements and four different precue conditions were possible. Letters were assigned as precues, each corresponding to one of the movement values within a parameter. For instance, "R" meant right arm, "F" meant forward direction, and "N" meant near extent. Typical precue combinations indicated that the right arm would be used (1 precue); or that the right arm would make a forward movement (2 precues); or that the right arm would make a forward movement to a near response key (3 precues); or the precue gave no prior knowledge about the intended movement (0 precues). The reaction stimuli were eight colored dots such that one color corresponded to one of the eight possible movements. For example, a red dot signalled subjects to execute a long movement in the forward direction with the left arm.

Rosenbaum argued that the precuing technique allowed one to answer a number of questions concerning the specification or programming of the movement parameters being studied. Questions that he

addressed included:

1) Are the programming times for different movement values within a parameter the same?
2) How long does it take to program each of the separate movement parameters?
3) Are the programming times of a particular parameter dependent on the programming requirements of another parameter?
4) Are movement parameters programmed in a strict serial order?
5) Is the programming of more than one parameter accomplished in a serial or parallel manner?

On a typical trial subjects were given a precue for three seconds and 500 msec later one of the eight colored dots appeared on a tachistoscopic display. The subject's task was to move as quickly as possible to the response target paired with this particular color. With eight movements and eight types of precues there were a total of 64 different trial possibilities. Each subject executed 12 replications of these trials over a two day period for a total of 768 trials. RT and movement time (MT) were the main dependent variables and errors in performance were also recorded.

Analysis of the data revealed a general increase in RT as the number of response parameters remaining to be programmed increased. In actuality this result is nothing more than the familiar increase in RT as a function of the number of response alternatives and was fully expected (Hick, 1952; Hyman, 1953). For the purposes of

programming, interest focused on the precue conditions that only allowed partial pre-programming; the two and one precue conditions. In the former, only one parameter remained unspecified prior to movement initiation and RT was viewed as the time to program this variable. The results showed that the specification times were longest for arm, shorter for direction, and shortest for extent. In the latter, two parameters remained unspecified prior to movement initiation, thus RT reflected the time to program combinations of parameters. The data revealed that specification times were longest for arm and direction, shorter for arm and extent, and shortest for direction and extent.

On the basis of these results, and others not to be presented, Rosenbaum concluded that arm was the most important programming variable and extent was the least important programming variable. Further, the programming of these three parameters was done serially, and arm and direction had no strict specification order, but both were programmed before extent.

Do these results really speak to response programming or MP construction? As the precuing method is currently presented, there is reason to question Rosenbaum's interpretation of his findings. It was previously stated that in HIP terms, response programming effects are generally considered to reflect operations in the response selection stage (Kerr, 1978). Presumably, Rosenbaum intended to manipulate this processing stage by the precuing technique. Serious doubts can be raised, however, about whether Rosenbaum's RT effects can be

attributed solely to response selection. The problem lies in using colors as "go" signals. To fully appreciate this position we must first examine the proposed processing stages within a HIP model. The model selected is one developed by Theios (1975) because it is one of the few HIP models that puts an emphasis on response organization stages.

The model consists of five operationally distinct processing stages: input, identification, response determination, response selection, and response output. The initial two stages are primarily perceptual in nature and for the present purposes are unimportant. They simply encode and identify stimulus information. Since it will be argued that Rosenbaum confounded response determination and response selection, these are the stages to be emphasized.

Once a stimulus has been identified (given a stimulus code or name), determination time is the time to determine what cognitive response is required (Theios, 1975). If the stimulus and response codes are highly compatible response determination time is minimal or insignificant. On the other hand, the less compatible these two codes are the more time it will take to complete the determination stage. A compatible situation, for example, would be naming letters of the alphabet, whereas, an incompatible situation would be depressing a designated response key whenever a specific letter was presented. In the naming task the stimulus itself conveys direct and immediate information about the necessary response. In the key press

task, however, the mapping between stimulus and response is indirect in that one must first determine which response key is associated with the stimulus before the necessary finger response can be made (e.g. "A" means depress right index finger). More specifically, a verbal code-position code translation must be performed before the actual motor response can be selected. This additional time between identification and response reflects operations within the determination stage (Teichner & Krebs, 1974; Theios, 1975).

After the appropriate cognitive response has been chosen (response determination), the associated motor response must be selected (response selection) and executed (response execution). While a cognitive response may be "move the right arm 12 cm to the left", response selection has the responsibility of organizing the motor commands that will execute the movement and translating them into a language compatible with the motor control system. In other words, there is a shift from a task-defined external perspective to one that is internal to the motor control system (Kerr, 1978). When the task-defined properties are maximally compatible with the actual response, there is no need for this additional re-coding process. As the degree of compatibility or directness decreases, however, the need for a translation increases (Fitts & Seeger, 1953), and this increase in processing time occurs in the response determination stage.

Although the utility of postulating two separate stages can be

questioned, a reasonable amount of evidence exists to support such a distinction (Fitts & Seeger, 1953; Theios, 1975; Welford, 1968). Perhaps the most compelling evidence has been provided by Teichner and Krebs (1974). They classified a large number of choice reaction tasks according to the kinds of transformations required between a stimulus and response. The four categories of tasks identified were: 1) digit-voice, 2) light-key, 3) digit-key, and 4) light-voice. Teichner and Krebs argued that the digit-voice task was highly developed in adults and because of this fact the stimulus had a direct mapping with the response. Therefore, it was considered the task requiring the least amount of stimulus-response translation. The light-key task was also a relatively compatible task since the position code for both the stimulus and response was the same. In contrast, the digit-key and light-voice tasks required a more extensive translation. The digit-key combination required a verbal-to-position translation and the light-voice combination required a position-to-verbal translation.

Teichner and Krebs' (1974) re-analysis of the results from these tasks demonstrated quite strikingly that stimulus-response coding relationships have a dramatic influence on RT's in CRT tasks covarying the number of response alternatives. The tasks requiring the least number of translations (digit-voice and light-key) generally showed the fastest RT's across all response alternative levels. The important point to be gained from the foregoing discussion is that the effects reported appear to be the result of stimulus-response coding

differences (Teichner & Krebs, 1974). Further, the effects of this incompatibility are localized in a processing stage immediately before response selection (Teichner & Krebs, 1974; Theios, 1975). Using Theios' terminology, this is the response determination stage.

Returning to the issue surrounding Rosenbaum's experiment, it is not altogether clear that the reported RT effects are programming in nature. The use of colored dots as "go" signals hardly created a compatible or direct mapping between the stimulus and response codes, and in fact created a situation that necessitated a verbal (color) code-to-position code translation. The utility of Rosenbaum's interpretations is further questioned by a series of experiments reported by Goodman and Kelso (Note 4). The exact same movement task was used and the same three movement parameters were manipulated, however, the manner in which responses were signalled was changed. Rather than using colored dots as "go" signals, a visual display was used whose configuration created a direct one-to-one mapping between "go" signals and response keys. The result of import was Goodman and Kelso's failure to obtain differential programming times among the three movement parameters: the times to program arm, direction, and extent were equivalent, as were the times to program combinations of movement parameters.

Since the latter study used a highly compatible spatial task, one can argue that response determination time was minimal (Fitts & Seeger, 1953; Teichner & Krebs, 1974; Theios, 1975) and that for the most part

RT reflected the operations within the response selection stage. That is, increases in RT when movement parameters were unknown prior to response initiation reflected increases in the programming operations of response selection. On the other hand, there can be no doubt that Rosenbaum's subjects had to perform a verbal code-to-position code translation prior to response selection. Consequently, increases in RT when movement parameters remained unspecified before initiation reflected the time to complete two processing stages: determination and selection. Therefore, one is unable to interpret these findings as strict instances of response programming, and further makes one question whether the observed RT differences resulted from purely response selection operations. In fact, based on Goodman and Kelso's data, the most reasonable conclusion is that the differential RT effects are localized in response determination and when determination time is eliminated the differential RT effects disappear.

An unresolved question, then, is to what extent do stimulus-response translations affect response programming operations? These translations undoubtedly increase RT, but can one conclude these effects are programming in nature and are they confined to the response selection stage? The aim, therefore, of the present investigation will be to systematically determine 1) if response determination and response selection are two independent processing stages and 2) how stimulus-response translations affect the programming of various movement parameters.

## GENERAL STATEMENT OF THE PROBLEM

Response programming studies usually operate under the assumption that the planning and organization processes within the response selection stage are being isolated (Kerr, 1978). The present investigation questions this assumption. It was pointed out earlier that in some instances there has been a confounding between the operations of the response determination and response selection stages. Whenever a stimulus fails to directly signal the required response, intermediate translations between the stimulus and response codes are necessary before the appropriate motor parameters can be specified (Fitts & Seeger, 1953). Such translations have been attributed to the response determination stage (Teichner & Krebs, 1974; Theios, 1975; Welford, 1968), yet within the response programming literature there has been no concern for maintaining a distinction between these two stages. The recent discrepancy between the results of Rosenbaum (in press) and those of Goodman and Kelso (Note 4), however, point out that the differing operations of these two processing stages can no longer be ignored. Using the movement parameters of direction and extent and the precuing technique, two experiments are conducted to demonstrate the functional differences between the processes within response determination and response selection. By varying the type of stimulus-response translation within the precuing paradigm, it will be possible to determine: 1) whether response determination and

response selection should be viewed as independent processing stages and 2) how intermediate translations influence the programming latencies of movement parameters.

Additive factor logic (Sternberg, 1969; Taylor, 1976) is used to address these issues. One of the basic premises of this method is that when two experimental factors interact (statistically), they are said to affect processing operations in a common stage. Thus, to support the contention that determination is a separate stage it is necessary to covary in a factorial design at least two variables hypothesized to influence determination time. Two such factors are spatial-motor compatibility and stimulus transformation (Teichner & Krebs, 1974; Theios, 1975; Welford, 1968).

In Experiment 1, the precuing task involves four translation conditions; spatial-motor compatible, spatial-motor incompatible, spatial transformation, and incompatible-spatial transformation. Since these factors are not thought to influence response selection, if they interact with each other support will be provided for the independence of determination and selection. Further, by the very nature of the precuing technique a third response determination factor is present in the experiment; set size (Smith, 1979; Theios, 1975). Set size is defined as the number of alternative responses possible on any given trial, and in the present context is dependent on the number and type of movement parameters remaining to be programmed. By considering the four translation conditions as levels of

compatibility, a significant set size by compatibility interaction contrast would also support the independent stage notion.

The effect of stimulus-response translations on the individual programming times of direction and extent can be examined by simply comparing the appropriate RT's within each translation condition. If a response selection process is responsible for Rosenbaum's (in press) differential programming effects, direction will have the longest programming latency in all four of these conditions. If, on the other hand, a response determination process is responsible for these effects no differential programming will be observed in the spatial-motor compatible condition, whereas, differential programming will be prevalent in the other three translation conditions. In the former, no translation is needed since the mapping between stimuli and responses is direct, but in the latter, some form of translation is required.

The above analyses are intended to use RT as the dependent measure. However, a more refined examination of the experimental questions is possible by partitioning RT into the actual times required for response determination and response selection. Response determination time can be analyzed for a set size by compatibility interaction contrast and differential programming. If determination is a separate stage, set size and compatibility will again interact. As for the Rosenbaum-Goodman and Kelso issue, if differential programming is found in determination time, but not

selection time, support would be found for the assertion that Rosenbaum's RT effects can not be attributed to response programming.

Experiment 2 is essentially a replication of the previous experiment, the only major difference being the practice level of subjects. Of specific interest is whether the RT and programming relationships observed in the previous experiment will change as a function of practice. Moreover, how the actual determination and selection times are affected by practice is also of interest. Teichner and Krebs (1974) argued that practice has its greatest influence over the speed of the translation process and relatively little influence on the response selection process. Support for this position, and further support that a translation must be made when the mapping between a stimulus and response is less than optimal, would be found if determination time shows a greater reduction from Experiment 1 to Experiment 2 than response selection time.

## EXPERIMENT 1

The purpose of this initial experiment is to more clearly define the relationship between stimulus translations, such as those required in Rosenbaum's (in press) experiment, and response programming. By combining the precuing technique with additive factor methodology (Sternberg, 1969; Taylor, 1976) it should be possible to address this issue. It is only necessary to select a second experimental variable also hypothesized to influence the response determination stage. Teichner and Krebs (1974) and Theios (1975) maintain that stimulus-response compatibility is such a factor, and if it can be shown that these two variables interact statistically, yet do not affect response selection, support will be found for the independent stage position. Unlike Rosenbaum's experiment, only two movement parameters are used, direction (left and right) and extent (near and far); thus, four rather than eight distinct movements are possible. Although the number of movements and precue conditions are reduced, it will be possible, none-the-less, to sufficiently test the experimental hypotheses.

Four translation groups are required to fully evaluate the previously stated experimental hypotheses. These groups are: 1) spatial-motor compatible (SMC), 2) spatial-motor incompatible (SMI), 3) spatial transformation (ST), and 4) incompatible-spatial

transformation (IST). The SMC condition is essentially the light-key task described by Teichner and Krebs (1974), in which the spatial relationship between movement stimuli and responses is direct. Movements are executed horizontally to the left or right and a visual display of movement lights is arranged in a horizontal fashion to provide a compatible one-to-one mapping. In this condition, determination time should be minimal, and it serves as a control or baseline measure of determination time. In the SMI condition, subjects are instructed to always move in the opposite direction and extent of that provided by the precue and movement stimuli. For example, if precued to move in the right direction, the actual movement direction is left. Further, if the "go" signal normally indicates a left far response, one moves to the right near response key. As for the ST condition, the spatial position of the movement stimuli are altered so that they no longer convey a direct correspondence with any of four responses. The movement light display is rotated to a vertical position and arbitrary assignments are given to the lights and responses: the two left response keys are paired with either the two top or bottom movement lights and the two right response keys are paired with the remaining two lights. In both the SMI and ST conditions, performance of the task only involves one of the factors said to affect determination time, and each, therefore, measures determination time for its respective variable. Finally, the IST condition requires the movement light display to be in the

vertical position, and in addition, the incompatibility rules are invoked. For instance, if the top light is paired with the left far movement, subjects will move to the right near response key. In this latter case, before the motor response can be programmed, one must first determine the arbitrary response signalled by the movement cue and then invoke the incompatibility rule. As a result, the IST condition measures the time to accomplish both of these determination processes.

With four such groups within a precuing framework, it will be possible to determine whether response determination and response selection are separate processing stages, determine how the programming latencies of direction and extent are influenced by stimulus-response translations, and determine if the programming of direction and extent is serial or parallel in nature. Analysis of these issues will be done using RT as the dependent measure, as well as with empirical estimates of response determination time and response selection time.

Teichner and Krebs (1974) developed a set of equations whereby these latter two times can be measured. First, one must assume that

$$CRT = a + T_{S-R} + c, \qquad (1)$$

where CRT = choice reaction time, a = the portion of CRT associated with stimulus encoding, $T_{S-R}$ = the time to complete any necessary stimulus-response translations, and c = the time to complete all activities associated with response selection. Equation 1 estimates

CRT in tasks that require some stimulus-response translation(s) and by rearranging this equation one can estimate the time to perform the translation and selection operations. One additional assumption, however, is that SRT = a. Providing one can accept such an assumption,

$$T_{S\text{-}R_T} + c_T = (CRT_T - SRT_T). \quad (1a)$$

Consideration of a spatial-motor compatible task yields a somewhat different equation since no stimulus-response translation activity is required;

$$CRT_c = a_c + c_c, \quad (2)$$

and by rearranging this equation one can estimate response selection time,

$$c = (CRT_c - SRT_c). \quad (2a)$$

By further combining equations 1a and 2a, one is able to isolate and estimate translation time:

$$T_{S\text{-}R} = (CRT_T - SRT_T) - (CRT_c - SRT_c). \quad (3)$$

In the present experiment a direct estimate of SRT will be provided by the 2 precue condition (no programming) since all information about the intended movement is known prior to response initiation. Thus, a method appears feasible for both the experimental manipulation of stimulus and response coding processes and for the experimental evaluation of the degree of stimulus-response compatibility (Teichner & Krebs, 1974). The spatial-motor compatible condition serves as the baseline, and by applying equations 1a, 2a, and 3,

determination and selection times will be empirically derived. Once these actual times have been obtained, determination can be evaluated for the independence of the response determination and response selection stages (via a set size by compatibility level interaction contrast), the differential programming of direction and extent, and the serial versus parallel processing of direction and extent; and selection can be evaluated for the differential programming of direction and extent, and the serial versus parallel programming of direction and extent.

## Method

Subjects. Eight volunteers (4 male, 4 female), ranging in age from 22 to 32, were recruited from the University of Wisconsin-Madison student population. Each subject was tested under all translation and precue conditions.

Apparatus. The apparatus consisted of a response panel, a visual display, and a MT clock (Figure 1A). The response panel (54 x 54 x 13 cm) contained five circular response keys situated 23 cm from the edge of the response panel (subject's view). The middle, home key, was 1.3 cm in diameter and all trials originated from this key. The remaining four movement keys were located 5 cm and 10 cm to the left and right of the home base, and they had target diameters of 1.3 cm and 2.6 cm. These target dimensions conformed to the specifications of Fitts Law (Fitts, 1954). Each key was




Figure 1A. Configuration of precues and movement light display for SMC and SMI.

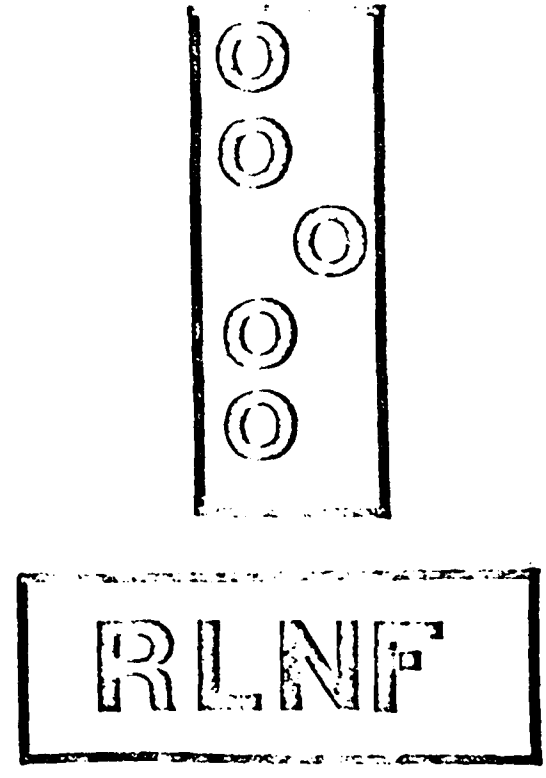



Figure 1B. Configuration of precues and movement light display for ST and IST.

connected to a microswitch (Microswitch model B2-2RW82-A2) that needed to be released (home key) or depressed (movement keys) by approximately 1 mm for the contacts to open or close. Further, during experimental trials subject's view of the response panel was shielded by a black cloth screen. The screen was designed to allow a free and unimpeded movement. The visual display was situated at eye level approximately 90 cm from the subject, and it consisted of two parts. The first was a single, horizontal row of four letters (RLNF) 1.4 cm wide, 1.3 cm high, and .8 cm apart. These letters served as direction (R= right; L= left) and extent (N= near; F= far) precues, and when illuminated each was easily distinguishable. The second aspect of the visual display contained the actual movement or reaction lights and was situated 8.5 cm above the precue letters. Five LED's (one red and four green) were aligned in a horizontal row that coincided with the response keys. The center, red, LED acted as a warning signal, and the remaining four LED's were movement signals. The warning light was .7 cm below the others, the near left and near right movement lights were .5 cm from the warning signal, and the far left and far right movement lights were 1.5 cm from the warning signal. These lights subtended subject's view at an angle of 2 degrees. This same display was used for the groups involving the spatial transformation and was rotated into a vertical position to provide the desired configuration (Figure 1b). A MT clock was also placed along side the visual display. The entire experimental

arrangement was interfaced with a Digital Equipment Corporation PDP8e computer that was programmed to sequence stimulus events, as well as record and perform preliminary data reduction of RT, MT, and performance errors.

Procedure. Prior to the start of the present experiment, each subject had participated in five to eight pilot or practice sessions which focused on learning the exact nature of the basic experimental requirements. Initially, movements were executed with the aid of vision, and after a subject was performing accurately under these conditions, sight of the response keys was precluded for the remaining sessions. When precues and movement lights were used, they always involved the compatible condition.

The sequence of events on any given trial was initiated by the subject depressing the home key, after which a precue was immediately presented. Subjects were instructed to use this precue information to prepare for the upcoming movement(s). Once the precue was known, subjects were instructed to fixate the warning signal for the remainder of the trial. The intent of this instruction was to reduce the significance of extraneous eye movements. After a two second precue period elapsed, a warning light was presented, and following a variable fore-period (600, 800, or 1000 msec) a movement light was illuminated. On the occurence of a movement light, the task was to release the home key and move to the specified response key as quickly and accurately as possible, after which feedback about MT

was provided. Further, subjects were told to remain in contact with the home key until they knew fully where they had to move. This instruction was included to ensure that all movement programming was completed prior to response initiation.

Since two movement parameters were manipulated, direction (right or left) and extent (near or far), four precue or programming conditions were possible. (For the sake of consistency and clarity, the term programming condition is preferred since it more accurately describes the actual operations that a subject had to complete after the "go" signal was presented.) The four programming conditions were: 1) program none, where both parameters were known prior to response initiation, 2) program extent, where direction was known and extent remained unspecified prior to initiation, 3) program direction, where extent was known and direction remained unspecified prior to initiation, and 4) program direction and extent, where no prior information was given, thus both parameters remained unknown prior to initiation.

A precue was given by simply illuminating the letter of the desired parameters(s). For example, in the program none condition, if the intended movement was near right, the "R" and "N" precues were presented; in the program extent condition, either an "R" or "L" was presented, providing only direction information; in the program direction condition, either an "N" or "F" was presented, providing only extent information; in the program direction and extent condition, all four letters were illuminated, providing no advance

*information about the upcoming movement.*

Four testing sessions were completed under each group, with the first designated as a practice session. Presentation order of translation conditions was different for each subject, and these were randomly chosen from the 24 possible orders. An experimental session began with a set of 10 warm-up movements made from the home base to each response key. These trials were executed without precues or "go" signals. In each testing session subjects received 7 blocks of 52 trials, and within a block, the 48 precue/movement/foreperiod combinations appeared once, along with four catch trials. On a catch trial the precue and warning signals were presented, but no movement was illuminated. One random sequence of 52 trials was stored in the computer, and the software was written so that the computer could be instructed to begin a testing session at any position in the sequence. This position was randomly varied each day. Once the start position was designated, trials were presented in an ascending order during odd numbered blocks and in a descending order during even numbered blocks. To avoid any possible learning of the trial sequence, a new random sequence of trials was introduced midway through the experiment. Whenever an error was committed, this trial was repeated at the end of the block in which it occurred. It was also repeated in the temporal order of occurence, and in the event an error was made on an error trial, it was repeated after all other error trials had been presented. Since trial presentation rate

was subject controlled, they were able to proceed through the session at their own pace. Subjects were, however, encouraged to complete a trial block before taking extended rest periods. On the average, one session lasted 50 minutes.

Three principal dependent measures were recorded on each trial. These were: 1) RT, defined as the time between the appearance of the movement light and the release of the home key; 2) MT, defined as the time between the release of the home key and the first depression of a response key; 3) Errors, defined as the release of the home key before the movement light was illuminated (movement error), depression of the incorrect response key (response key error), a MT greater than 200 msec (movement time error), and a RT greater than that established a priori for each group (reaction time error). The maximum MT was set at 200 msec because pilot data suggested that movements were well within this range, and at the same time it was difficult to initially move toward an incorrect target and still re-adjust the movement for the correct key in this time period. Since the difficulty level of the four translation conditions was clearly different, it was deemed necessary to establish different maximum RT's for each group. Here again, pilot data were used to aid in establishing appropriate cut-offs. On Day 1, the maximum RT's for the SMC, SMI, ST, and IST conditions were 500, 800, 700, and 1000 msec's, and in the subsequent sessions the maximum RT's were 400, 600, 500, and 700 msec's, respectively. Each subject was constantly reminded to keep total

error rates for a session below 10%, and in any session that error rates became too large, it was terminated and repeated the following day.

Design and analyses. The experimental design was within subjects such that all factors were completely crossed. The data were analyzed using a 8 x 4 x 4 x 2 x 2 x 3 (subjects x translation x programming x direction x extent x days) analysis of variance. Although a number of significant main effects and interactions can be obtained from a six factor design, interest with regard to the experimental questions focused on the translation x programming interaction. Due to the amount of data collected, other significant results are discussed only when they directly address the theoretical issues under study. In the interest of completeness, however, the entire analysis of variance tables for all dependent measures can be found in the Appendices.

Reaction time analyses -- The independence of determination and selection was examined via two sets of interaction contrasts. The first was a SMC x ST contrast. Four such contrasts were computed, one for each programming condition, such that the difference in means between SMC and SMI was compared to the difference in means between ST and IST. The second was a set size x compatibility level interaction contrast. This interaction contrast compared two choice when extent was uncertain, two choice when direction was uncertain, and four choice when direction and extent were uncertain across the

four levels of compatibility. Differential programming involved a test of simple main effects of the four means within a translation group (program none, program extent, program direction, and program direction and extent). Finally, with respect to serial versus parallel programming, the difference in means between program none and program extent were compared to the difference in means between program direction and program direction and extent.

Response selection and response determination time analyses -- The same three theoretical issues were addressed for determination time. The independence notion was tested via a set size x compatibility interaction, differential programming was tested via a simple main effects analysis, and serial versus parallel processing was tested via the comparison described above. For selection time, the two issues that could be addressed were differential programming and serial versus parallel programming, and these were tested in the same manner previously described.

## Results

Error rates. With respect to the 10% criterion established at the outset of the experiment, two subjects exceeded this limit (one in the SMI condition and one in the IST condition) and were required to repeat this session. The error rates discussed below have been categorized according to one of the four error types and are presented in Table 1 (percentages). Movement errors (move off home key

too early) and RT errors (RT above the maximum allowed) were below 1% for all translation by programming condition combinations. Response key errors (hit wrong response key) were less than 3%: Further, there was a general tendency for errors to increase as the degree of translation increased and as the number of movement parameters to be programmed increased. In both instances, however, these changes were slight, with the largest increase across translation conditions = 2.6% and across programming conditions = 2.1%. These same patterns were also evident in movement time errors (MT above maximum allowed), but again the changes were small; 1.2% and 2.1% for translation and programming conditions. Although shifts in error rates are usually an unwelcomed characteristic in RT data, the present increases do not appear to be sufficiently large enough to create any problems with respect to interpreting the data. Moreover, in most instances the translation by programming combinations with the largest error rates, also had the largest RT's. Thus, any contamination of the data by speed-accuracy trade-offs can be ruled out.

Movement time analysis. The results of an analysis of variance on MT are provided in Appendix A-1. The means and standard deviations for translation, programming, and days are presented in Table 2. For the ease of presentation and the sake of clarity, probability values for individual effects or comparisons are not presented in the text. Rather, each effect or comparison was tested with $\alpha = .05$, and

Table 1

Error Rate Profile (percentages) for each Error Type in Experiment 1

| | Movement Error | | | | Response Key | | | | Reaction Time | | | | Movement Time | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PROGRAM | SMC | SMI | ST | IST | SMC | SMI | ST | IST | SMC | SMI | ST | IST | SMC | SMI | ST | IST |
| NONE | 0.4 | 0.3 | 0.2 | 0.0 | 0.0 | 0.6 | 0.3 | 0.8 | 0.2 | 0.1 | 0.1 | 0.1 | 2.5 | 3.1 | 1.8 | 2.1 |
| EXTENT | 0.1 | 0.0 | 0.0 | 0.1 | 0.3 | 3.7 | 1.0 | 2.9 | 0.4 | 0.4 | 0.2 | 0.1 | 2.8 | 4.2 | 3.0 | 3.4 |
| DIRECTION | 0.1 | 0.0 | 0.0 | 0.0 | 0.3 | 0.9 | 1.3 | 2.2 | 0.2 | 0.5 | 0.6 | 0.3 | 2.8 | 3.6 | 3.3 | 2.8 |
| DIRECTION AND EXTENT | 0.0 | 0.0 | 0.0 | 0.0 | 0.6 | 2.0 | 1.7 | 2.9 | 0.6 | 0.5 | 0.7 | 0.5 | 2.5 | 4.5 | 3.9 | 3.7 |

N per cell = 2106

Table 2

Movement Time Means (msec) and Standard Deviations of
Translation Conditions, Programming Conditions, and Days in Experiment 1

| | | Spatial-Motor Compatible | | | | Spatial-Motor Incompatible | | | | Spatial Transformation | | | | Incompatible-Spatial Transformation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | P(N) | P(E) | P(D) | P(DE) | P(N) | P(E) | P(D) | P(DE) | P(N) | P(E) | P(D) | P(DE) | P(N) | P(E) | P(D) | P(DE) |
| DAY 1 | $\bar{X}$ | 82 | 86 | 88 | 89 | 80 | 87 | 85 | 90 | 83 | 87 | 88 | 92 | 80 | 87 | 87 | 87 |
| | SD | 10 | 9 | 9 | 9 | 9 | 11 | 9 | 12 | 10 | 10 | 12 | 13 | 9 | 11 | 10 | 11 |
| DAY 2 | $\bar{X}$ | 81 | 84 | 86 | 89 | 83 | 90 | 89 | 91 | 81 | 85 | 86 | 90 | 81 | 86 | 86 | 87 |
| | SD | 9 | 9 | 8 | 9 | 8 | 11 | 10 | 10 | 9 | 11 | 11 | 11 | 9 | 11 | 10 | 11 |
| DAY 3 | $\bar{X}$ | 80 | 84 | 85 | 87 | 80 | 86 | 85 | 88 | 81 | 85 | 86 | 88 | 79 | 84 | 84 | 86 |
| | SD | 5 | 9 | 10 | 10 | 9 | 11 | 10 | 11 | 9 | 10 | 10 | 11 | 9 | 10 | 9 | 11 |

P(N) = program none
P(E) = program extent
P(D) = program direction
P(DE) = program direction and extent

Table 3

Reaction Time Means (msec) and Standard Deviations of
Translation Conditions, Programming Conditions, and Days in Experiment 1

| | | Spatial-Motor Compatible | | | | Spatial-Motor Incompatible | | | | Spatial Transformation | | | | Incompatible-Spatial Transformation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | P(N) | P(E) | P(D) | P(DE) | P(N) | P(E) | P(D) | P(DE) | P(N) | P(E) | P(D) | P(DE) | P(N) | P(E) | P(D) | P(DE) |
| DAY 1 | $\bar{X}$ | 226 | 257 | 264 | 284 | 233 | 355 | 354 | 401 | 230 | 278 | 288 | 320 | 244 | 377 | 413 | 448 |
| | SD | 25 | 26 | 27 | 29 | 29 | 48 | 53 | 46 | 24 | 29 | 34 | 35 | 32 | 49 | 62 | 47 |
| DAY 2 | $\bar{X}$ | 227 | 259 | 263 | 280 | 239 | 350 | 352 | 393 | 222 | 269 | 279 | 317 | 243 | 363 | 393 | 431 |
| | SD | 23 | 24 | 26 | 24 | 30 | 42 | 48 | 42 | 21 | 27 | 29 | 34 | 37 | 48 | 60 | 47 |
| DAY 3 | $\bar{X}$ | 228 | 256 | 260 | 275 | 237 | 340 | 340 | 377 | 223 | 267 | 280 | 311 | 238 | 347 | 377 | 416 |
| | SD | 22 | 25 | 25 | 25 | 25 | 39 | 44 | 38 | 23 | 27 | 29 | 31 | 31 | 41 | 47 | 45 |

P(N) = program none
P(E) = program extent
P(D) = program direction
P(DE) = program direction and extent

unless specified otherwise, when the probability of significance was below this value it was considered significant and when above this value it was considered non-significant. The main effects of programming conditions, direction, and extent were significant, $F(3,21) = 12.54$, $F(1,3) = 17.05$, and $F(1,3) = 395.40$, whereas, the main effects of translation conditions and days were non-significant, $F(3,21) < 1$ and $F(2,14) = 2.80$. Post hoc analysis of the programming main effect revealed that MT in the program none condition (81 msec) was faster than MT's in the program extent (86 msec), program direction (86 msec), and program direction and extent (89 msec) conditions, and that MT's in these latter three conditions were equivalent. In addition, the direction main effect showed MT's to the right response keys (80 msec) were faster than to the left response keys (91 msec), and the extent main effect showed MT's to the near response keys (71 msec) were faster than to the far response keys (100 msec).

The direction by extent interaction was also significant, $F(1,3) = 16.77$. Further analysis revealed that MT's were fastest to slowest in the following order: RN(68 msec), LN(76 msec), RT (93 msec), LF(107 msec). One final interaction was also significant, the translation, direction, days interaction, however, no subsequent analysis was done because no substantive meaning could be discerned from its interpretation.

Reaction time analyses. All tests of the theoretical questions involved either simple or complex comparisons of means within the translation by programming conditions interaction. Therefore, specific interest was directed to this interaction, and all other significant effects were considered secondary, unless they contributed to the clarification of a particular theoretical issue. The RT means and standard deviations of translation conditions, programming conditions, and days are presented in Table 3. The translation by programming conditions interaction was significant, $F(9,63) = 20.81$, thus, the issues of independence, differential programming, and serial versus parallel programming were examined more closely.

Independence of selection and determination -- Two sets of interaction contrasts were computed using Scheffe's procedure to ascertain if response selection and response determination were independent processing stages. The first set of contrasts (compatibility by transformation) involved the four translation condition means within each programming condition; each failed to reach significance as shown in Figure 2 and Table 4. The second set of contrasts (set size by compatibility level) involved comparisons of two-choice extent versus four-choice direction and extent, and two-choice direction versus four-choice direction and extent for all combinations of the four compatibility levels (SMC-SMI, SMC-ST, SMC-IST, SMI-ST, SMI-IST, ST-IST). These data are presented in Figure 3 and Table 5. Of the twelve contrasts, only SMC-IST for extent was significant and

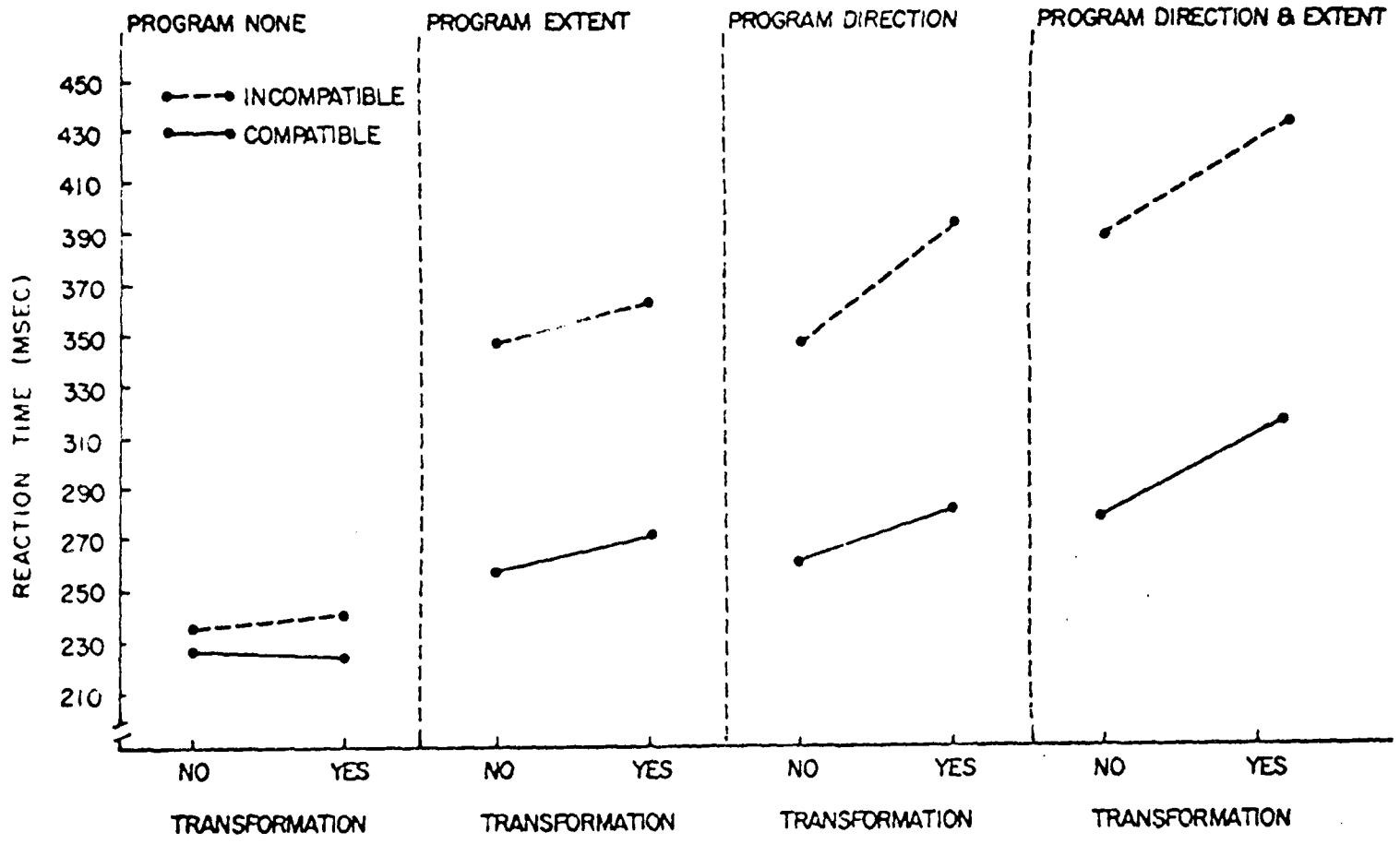



**Figure 2.** Mean RT (msec) of the compatibility by transformation interaction contrasts within each programming condition.

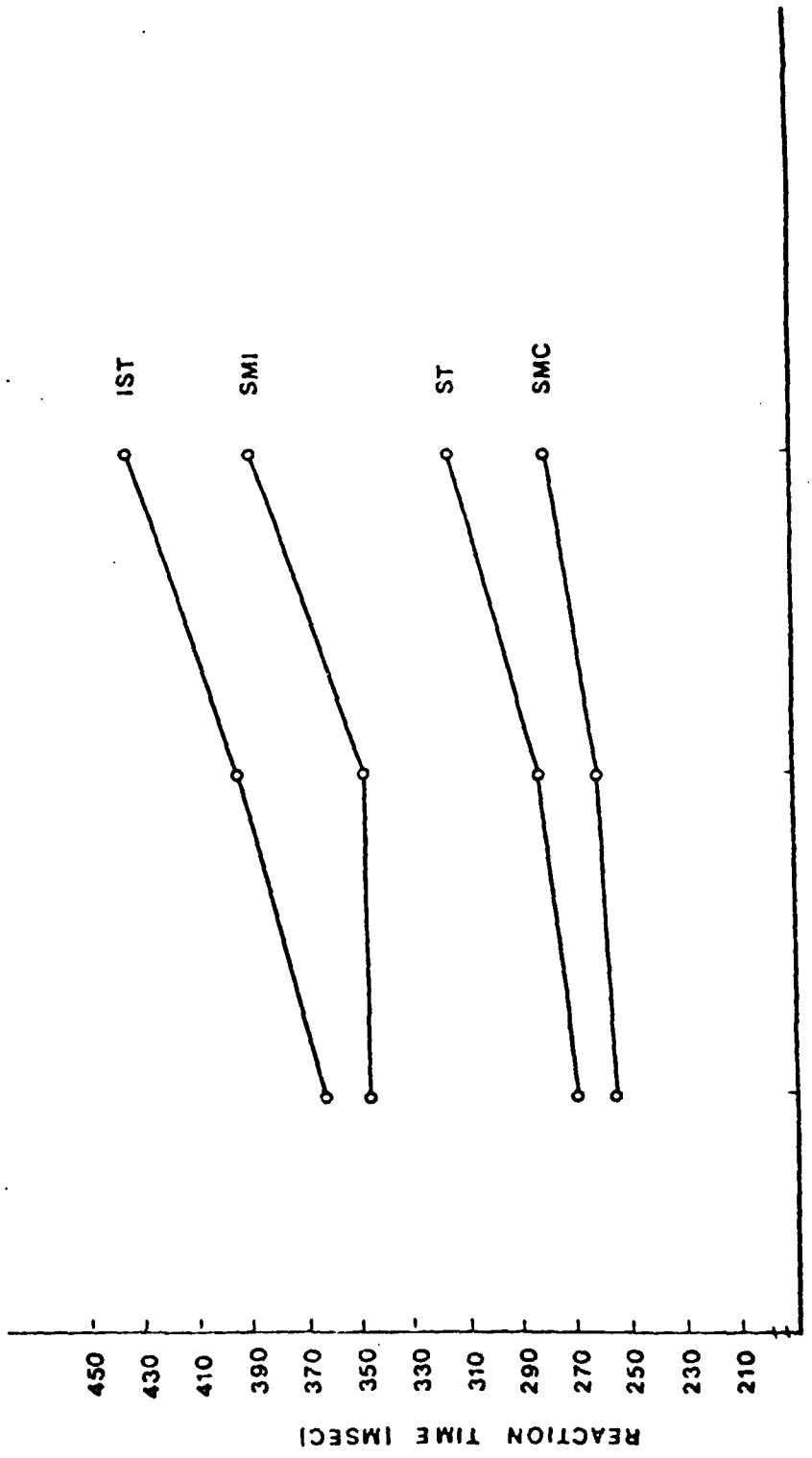



Figure 3. Mean RT (msec) of the set size by compatibility level interaction contrasts.

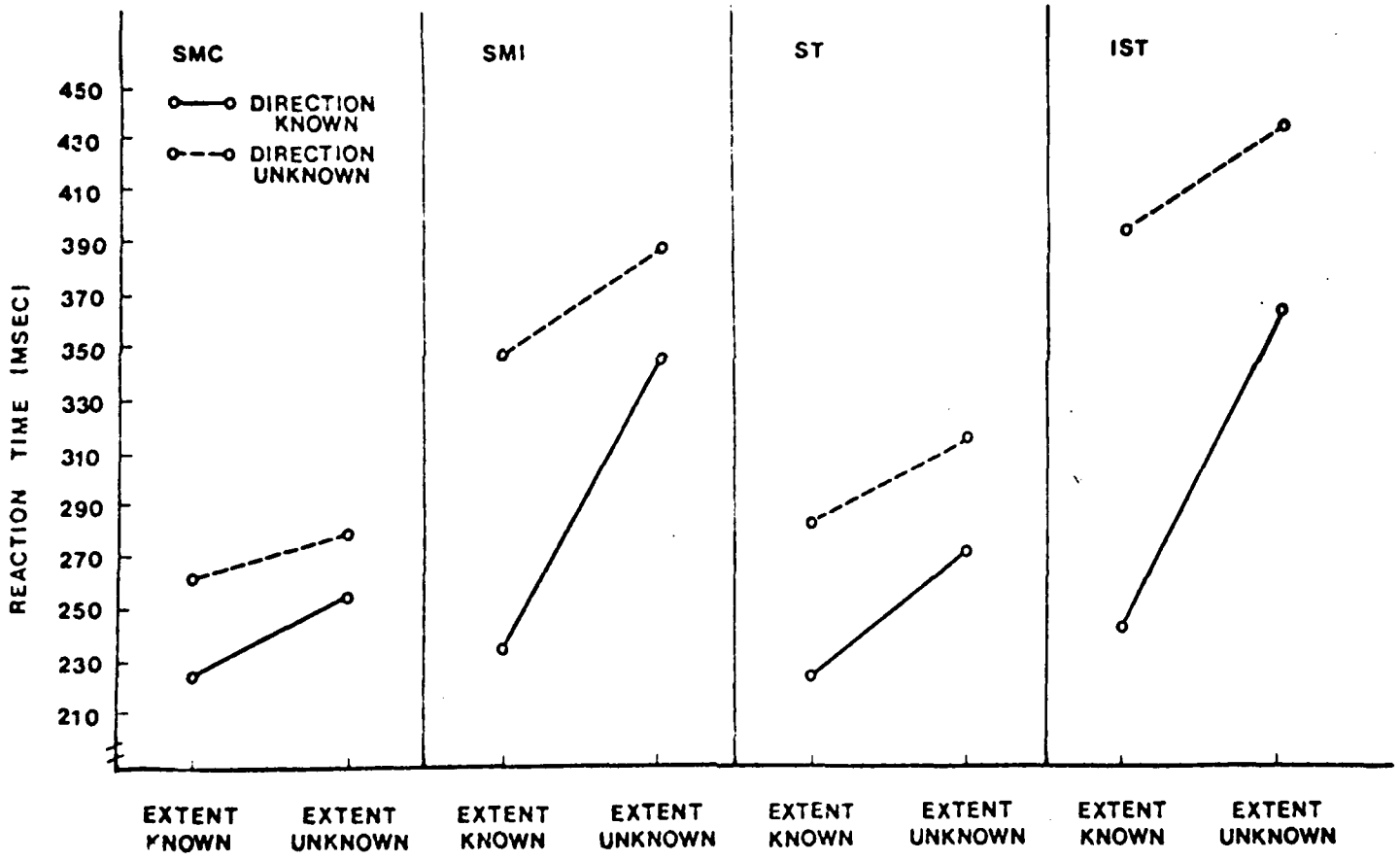



Figure 4. Mean RT (msec) of the four programming conditions within each translation condition.

Table 4

Compatibility-Transformation Interaction Contrasts for RT in Experiment 1 (Means in msec)

| | SMC | | SMI | | ST | | IST | | $\bar{D}$ |
|---|---|---|---|---|---|---|---|---|---|
| Program None | (227 | - | 237) | - | (225 | - | 242) | = | 7 |
| Program Extent | (258 | - | 348) | - | (271 | - | 362) | = | 1 |
| Program Direction | (263 | - | 349) | - | (282 | - | 394) | = | 26 |
| Program Direction and Extent | (280 | - | 389) | - | (316 | - | 432) | = | 7 |

this contrast showed a pattern of overadditivity.

Differential programming -- A simple main effects analysis was used to compare the four programming condition means within each translation condition (see Figure 4). The outcome of these tests were significant and subsequent analysis of pairwise differences were computed using Tukey's HSD procedure. For SMC, RT in the program none condition (227 msec) was faster than the program extent (258 msec), program direction (263 msec), and program direction and extent (280 msec) conditions, while RT's in these latter conditions were equivalent. For SMI, program none (237 msec) had the fastest RT, program extent (348 msec) and program direction (349 msec) were slower, but equivalent, and program direction and extent (389 msec) had the slowest RT. For ST, similar results were found: program none (225 msec) was fastest, program extent (271 msec) and program direction (282 msec) were slower, but equivalent, and program

Table 5

Set Size - Compatibility Level Interaction Contrasts for RT in Experiment 1 (Means in msec)

| 2 choice P(E) | 4 choice P(DE) | $\overline{D}$ | 2 choice P(D) | 4 choice P(DE) | $\overline{D}$ |
|---|---|---|---|---|---|
| SMC (258 - 348) | SMC (280 - 389) | = 19 | SMC (263 - 349) | SMC (280 - 389) | = 23 |
| SMC (258 - 271) | SMC (280 - 316) | = 23 | SMC (263 - 282) | SMC (280 - 316) | = 17 |
| SMC (258 - 362) | SMC (280 - 432) | = 48* | SMC (263 - 394) | SMC (280 - 432) | = 21 |
| SMI (348 - 271) | SMI (389 - 316) | = 4 | SMI (349 - 282) | SMI (389 - 316) | = 6 |
| SMI (348 - 362) | SMI (389 - 432) | = 29 | SMI (349 - 394) | SMI (389 - 432) | = 2 |
| ST (271 - 362) | ST (316 - 432) | = 25 | ST (282 - 394) | ST (316 - 432) | = 4 |

* $p < .05$

P(E) = program extent, P(D) = program direction, P(DE) = program direction and extent

direction and extent (316 msec) was slowest. Finally, in the IST condition, RT was fastest for the program none condition (242 msec), slower for the program extent condition (362 msec), slower yet for the program direction condition (394 msec), and slowest for the program direction and extent condition (432 msec).

Serial versus parallel programming -- The four means within a translation condition were also subjected to an interaction contrast analysis where the difference in RT between program none and program extent was compared to the difference in RT between program direction and program direction and extent (see Figure 4 and Table 6). These contrasts were significant for SMI and IST and were under-additive in nature. On the other hand, for SMC and ST these contrasts were non-significant.

Table 6

Programming Conditions Interaction Contrasts for RT in Experiment 1 (Means in msec)

| | P(N) | | P(E) | | P(D) | | P(DE) | | $\bar{D}$ |
|---|---|---|---|---|---|---|---|---|---|
| SMC | (227 | - | 258) | - | (263 | - | 280) | = | 14 |
| SMI | (237 | - | 348) | - | (349 | - | 389) | = | 71* |
| ST | (225 | - | 271) | - | (282 | - | 316) | = | 12 |
| IST | (242 | - | 362) | - | (394 | - | 432) | = | 82* |

*$p < .05$

P(N) = program none, P(E) = program extent, P(D) = program direction, P(DE) = program direction and extent

Response selection time analyses. Based on the rationale and equations presented earlier, RT was partitioned in such a way that it provided an estimate of response selection time. This new data set was then examined for differential programming and serial-parallel programming. Response selection times for extent ($RS_E$), direction ($RS_D$), and direction and extent ($RS_{DE}$) are depicted in Figure 5. For purposes of the experimental hypotheses interest focused on the programming conditions main effect, which was significant, $F(2,14) = 38.75$. The outcome of the differential programming analysis (Tukey's HSD procedure) revealed that $RS_E$ (31 msec) and $RS_D$ (35 msec) were equivalent, but, both were significantly lower than $RS_{DE}$ (53 msec). The serial-parallel issue was examined via a complex comparison ($RS_E + RS_D$ versus $RS_{DE}$) with Scheffe's procedure. This test yielded a significant effect and the RT pattern was of an underadditive variety.

Response determination time analyses. Just as it was possible to compute an estimate of selection time, it was possible to compute an estimate of response determination time for extent ($RD_E$), direction ($RD_D$), and direction and extent ($RD_{DE}$) in each of the three translation conditions. These times are presented in Figure 6 and Table 7. The translation by programming conditions interaction was significant, $F(4,28) = 2.72$. Post hoc inspection of the set size-compatibility level interaction contrast revealed that only one contrast was significant; SMI-IST for extent.

Table 7

Set Size - Compatibility Level Interaction Contrasts for Response Determination Time in Experiment 1 (Means in msec)

| 2 choice P(E) | | | 4 choice P(DE) | | | $\bar{D}$ | 2 choice P(E) | | | 4 choice P(DE) | | | $\bar{D}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SMI | - | ST | SMI | - | ST | | SMI | - | ST | SMI | - | ST | |
| (80 | - | 15) | (99 | - | 38) | = 4 | (76 | - | 21) | (99 | - | 38) | = 6 |
| SMI | - | IST | SMI | - | IST | | SMI | - | IST | SMI | - | IST | |
| (80 | - | 89) | (99 | - | 137) | = 29* | (76 | - | 116) | (99 | - | 137) | = 2 |
| ST | - | IST | ST | - | IST | | ST | - | IST | ST | - | IST | |
| (15 | - | 89) | (38 | - | 137) | = 25 | (25 | - | 116) | (38 | - | 137) | = 4 |

P(E) = program extent, P(D) = program direction, P(DE) = program direction and extent * $p < .05$

With regard to differential response determination time, in SMI, translation times for $RD_E$ (80 msec) and $RD_D$ (76 msec) were equivalent and both were significantly faster than translation time for $RD_{DE}$ (99 msec); in ST, translation times for $RD_E$ (15 msec) and $RD_D$ (21 msec) were similar and only $RD_E$ was faster than $RD_{DE}$ (38 msec); and in IST, translation time for $RD_E$ (89 msec) < $RD_D$ (116 msec) < $RD_{DE}$ (137 msec). Determination time was also examined for serial versus parallel processing via a complex comparison ($RD_E + RD_D$ versus $RD_{DE}$). For IST, this comparison was significant and showed an underadditive pattern. For SMI and ST this interaction was non-significant, however, inspection of SMI revealed a tendency for underadditivity, while ST showed a pattern more in line with seriality (see Table 7).

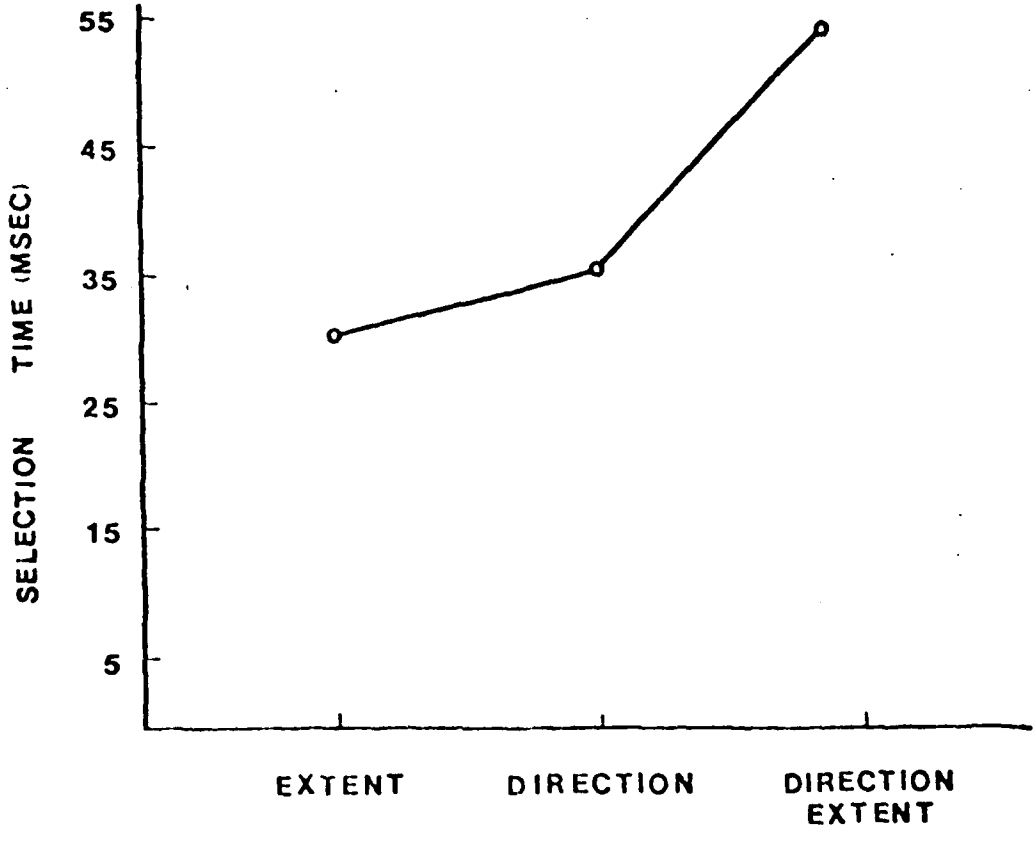



Figure 5. Mean response selection time (msec) of each programming condition.

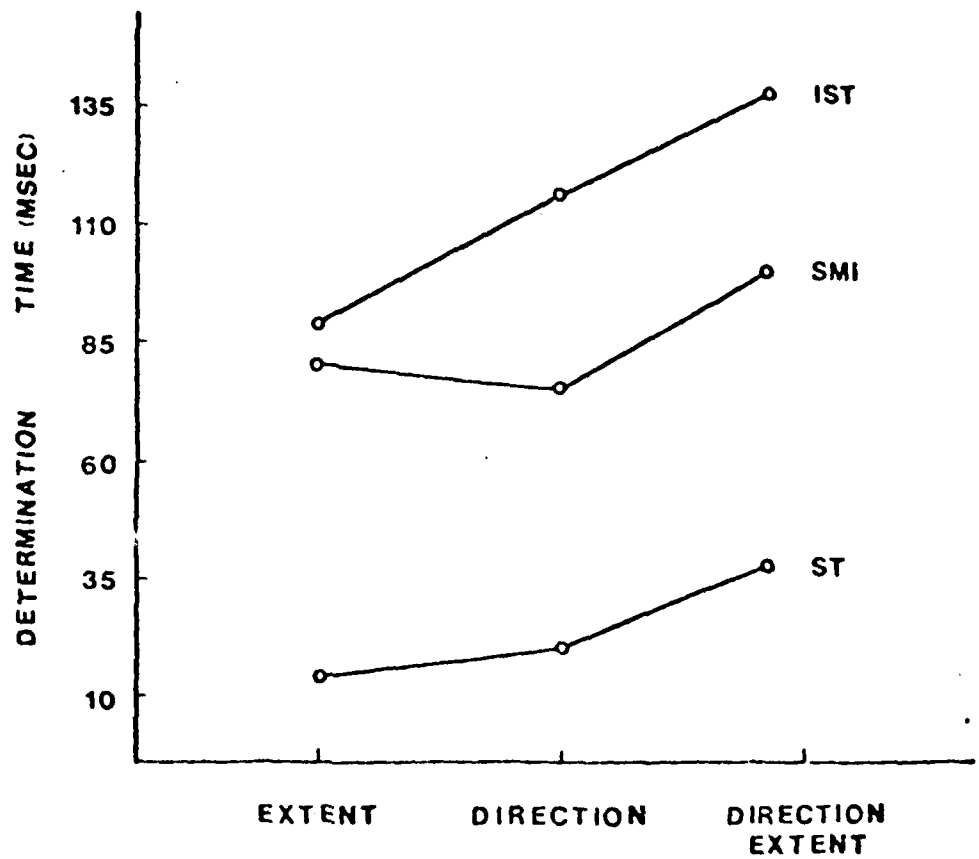



Figure 6. Mean response determination time (msec) of translation and programming conditions.

## Discussion

The primary objective of the present experiment was to determine if the differential RT's among movement parameters, as reported by Rosenbaum (in press), can be interpreted as viable response programming effects. The assertion was made that Rosenbaum used a task which necessarily required intermediate translations between the stimulus and response. As a consequence, his reported RT effects are inextricably confounded with two processing stages; response determination and response selection. Since determination is usually not considered part of the response programming process (Kerr, 1978) interpretations about response programming and MP construction based on this data are tenuous. To empirically justify such a conclusion an additive factor experiment was designed to illustrate that 1) determination and selection are separate processing stages and 2) the presence or absence of a stimulus-response translation is the factor responsible for the differential RT effects between movement parameters.

It was quite obvious, however, that scant evidence was generated in support of these experimental hypotheses. Considering the independence issue, for RT the compatibility-transformation interaction contrasts were non-significant, and for both RT and determination time, the set size-compatibility level interaction contrasts were, for the most part, non-significant. Such findings suggest that either these factors influenced separate processing stages or that these

results were partially or wholly confounded with an uncontrolled factor(s) that interacted with groups and programming conditions. This latter possibility will be considered in more detail after briefly discussing the differential programming and serial-parallel programming findings.

With respect to differential programming between extent and direction, the suggestion was made that the presence of a stimulus-response translation would result in a longer programming time for direction relative to extent, whereas the absence of such a translation would result in equivalent programming times for these two movement parameters. Let us first consider the RT data. When the mapping among stimului and responseswas direct (the SMC condition), and thus no translation, the times to program extent and program direction were not significantly different (258 msec versus 263 msec). Such a finding is consistent with the Goodman and Kelso (Note 4) data. Of the translation conditions, only 1ST yielded a significant difference (program extent = 362 and program direction = 394), although the non-significant pattern in ST favored this finding (program extent = 271 and program direction = 282). Thus, even though the type of translation required in the present experiment was different in nature from that in Rosenbaum's experiment (spatial as opposed to verbal) the differential RT effect was found, at least for the most difficult translation group.

Additionally, the response selection time and response

determination time analyses corresponded to the RT findings. In selection time, program extent and program direction were equivalent (31 msec versus 35 msec), whereas, in determination time for IST program extent was faster than program direction (89 msec versus 116 msec). Although one is unable to conclude that determination and selection are distinct processing stages, these latter findings indicate that the differences found in RT are attributable to stimulus-response translation and not motoric programming operations. In general, then, the outcome of the differential programming analyses provide a partial account of the differences noted between Rosenbaum (in press) and Goodman and Kelso (Note 4). At the very least, the present results point out that irrespective of processing stages, when the direct mapping between a stimulus and its associated response is disrupted overall RT includes a considerable translation component. A comparison of selection and determination time illustrates this fact very clearly (refer to Tables 15 and 16 on page 97 ), in that the translation times consumed a much larger proportion of CRT than did selection times in the SMI and IST conditions.

The final question of interest focused on the serial-parallel nature of programming extent and direction. RT indicated that in the SMC and ST conditions programming was accomplished serially, whereas, in the SMI and IST conditions programming was accomplished simultaneously or in parallel. It is worth noting that although non-significant, the pattern of results in both SMC and ST favored a parallel

programming position. Response selection time and response determination time showed analogous findings. Response selection time, which is an estimate computed from the SMC condition, supported a parallel interpretation, as did the IST estimate of response determination time. Seriality clearly held for the ST condition, however, the non-significant pattern for the SMI condition favored parallel processing. These results also conflict with Rosenbaum (in press) because he maintained that extent and direction had a serial programming relationship.

Irrespective of the differential programming and serial-parallel findings, the most striking aspect of the present experiment is undoubtedly the virtual lack of support for the independence of response determination and response selection. It was alluded to earlier that perhaps some extraneous factor was responsible for this state of affairs. To evaluate the extent of such a possibility, the entire data set was examined in more detail. This post hoc examination did indeed uncover an unwanted source of variance. Translation conditions and programming conditions interacted with days, $F$ (18,126) = 2.63. A more detailed analysis of this interaction revealed it to be primarily caused by the three conditions requiring a translation. In the SMC condition and the program none condition of the three translation conditions, RT was relatively stable across days. In contrast, for SMI, ST, and IST significant decreases in RT occurred across days in the program extent, program direction, and program

direction and extent conditions, as well as the program direction and extent condition in the SMC condition. Such a finding indicates that performance in the three latter translation conditions was improving across the three experimental testing sessions, while RT in the SMC condition reached a reasonable level of asymptotic performance. This result most likely occurred because of the greater experience in the SMC task (recall that each subject participated in 5-8 training sessions, each involving the SMC condition) and the more difficult nature of the task in the SMI, ST, and IST conditions.

Nevertheless, in the present context such a situation creates a definite interpretive problem because it could very likely mask the real operating characteristics and relationships of the processes being studied. Moreover, one is unable to assume that the observed relationships will remain constant after the differential effects of practice are eliminated. In fact, Shiffrin and Schneider (1977) suggest that practice or experience has a definite influence on the operating characteristics of certain cognitive processes. Consequently, the reliability of the data and validity of any interpretations or conclusions based on these data must be questioned and accepted with reservation.

Before any definite conclusions can be made about the experimental hypotheses under study, it will be necessary to eliminate this contaminating factor from the data. The primary objective of Experiment 2, therefore, is two-fold: 1) eliminate the significance

attributed to differential practice and 2) re-test the stated experimental hypotheses. It was decided that the most efficient and straightforward attack on this problem would be to replicate completely this initial experiment using the same subjects.

## EXPERIMENT 2

In the previous experiment it was evident that performance in the four translation conditions was differentially affected by practice. This fact was apparent in the significant translation, programming, and days interaction. As a result, it is difficult to evaluate how closely the previous findings reflect the processing operations of and the relationships between determination and selection. Therefore, in an attempt to eliminate this differential effect, primarily found in the translation conditions, the initial experiment was repeated. A second purpose of this replication was to ascertain the degree to which determination time and selection time are affected by practice. Since determination time is perhaps more significant than selection time in tasks where the direct stimulus-response mapping is disrupted, Teichner and Krebs (1974) argued that the former will be reduced to a greater degree than the latter. If such speculation is correct, it would provide additional support, indirect in nature, that translation and selection processes are independent operations.

### Method

Subjects. Seven subjects from Experiment 1 agreed to continue their participation in this second experiment and each was compensated with $20 for their services.

Apparatus. The apparatus and experimental arrangement were identical to that described in Experiment 1.

Procedure, design, and analyses. In most respects, the experimental procedures, design, and intended data analyses were congruent with those from the previous experiment. There were, however, three modifications of the procedures and design. First, the method for setting the allowable maximum RT on any given trial was changed. Rather than maintaining a constant maximum for all subjects in all testing sessions, the maximum was individually determined for every subject with each new testing session. The maximum RT on Day 1 was the same as in Experiment 1, but on each successive day the maximum RT was determined by the largest RT from the previous day. For example, the maximum RT on Day 2 was set at two standard deviations above the largest RT from Day 1. Second, the maximum allowable MT was reduced from 200 msec to 180 msec. Third, the presentation order of ST and IST was no longer counterbalanced. In Experiment 1 there was some evidence (nonsignificant) that subjects who received IST before ST had different RT patterns in these conditions relative to those who had been given a ST-IST order. To circumvent any potential significant effects, counterbalancing between these two conditions was disregarded. Subjects were randomly presented SMC and SMI, followed by ST and IST.

## Results

Error rates. All subjects stayed within the bounds of 10%, thus, no sessions had to be repeated. The error rate profiles (in percentages) for each error type are presented in Table 8. Movement errors were virtually non-existent and were no greater than .3%. Reaction time errors were more frequent than in Experiment 1, with the largest rate = 2%, however, such a result was most likely a function of the more conservative method of establishing the maximum RT. In addition, there was no evidence that these errors increased with translation difficulty and the largest increase across a programming condition was only 1.9%. Both response key and movement time errors tended to increase slightly as translation difficulty and programming uncertainty increased. But again, such changes were slight, with the largest difference being 3.1%. Therefore, it seems unwarranted to be concerned about differential error rates and the interpretability problems usually associated with them.

Movement time analysis. The results of an analysis of variance are provided in Appendix A-2. The means and standard deviations for translation conditions, programming conditions, and days are presented in Table 9. As in the initial experiment, the alpha level for all tests of significance was set as .05, and probability values below this level were considered significant, whereas, those above this level were considered non-significant. The main effects that reached significance were programming conditions, $F(3,18) = 19.06$,

Table 8

Error Rate Profile (percentages) for each Error Type in Experiment 2

| | Movement Error | | | | Response Key | | | | Reaction Time | | | | Movement Time | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PROGRAM | SMC | SMI | ST | IST | SMC | SMI | ST | IST | SMC | SMI | ST | IST | SMC | SMI | ST | IST |
| NONE | 0.0 | 0.3 | 0.1 | 0.1 | 0.3 | 1.1 | 0.8 | 1.5 | 0.2 | 0.5 | 0.1 | 0.3 | 2.9 | 2.6 | 2.2 | 2.3 |
| EXTENT | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 3.2 | 1.4 | 3.2 | 0.5 | 0.6 | 0.5 | 0.4 | 2.4 | 3.1 | 2.9 | 3.2 |
| DIRECTION | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 1.4 | 1.6 | 2.8 | 0.9 | 0.6 | 0.6 | 1.0 | 2.6 | 3.9 | 4.1 | 3.9 |
| DIRECTION AND EXTENT | 0.0 | 0.0 | 0.0 | 0.0 | 0.4 | 2.2 | 3.1 | 3.5 | 1.4 | 1.6 | 2.0 | 1.8 | 2.7 | 5.2 | 3.9 | 4.7 |

N per cell = 1764

Table 9

Movement Time Means (msec) and Standard Deviations of
Translation Conditions, Programming Conditions, and Days in Experiment 2

| | | Spatial-Motor Compatible | | | | Spatial-Motor Incompatible | | | | Spatial Transformation | | | | Incompatible-Spatial Transformation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | P(N) | P(E) | P(D) | P(DE) | P(N) | P(E) | P(D) | P(DE) | P(N) | P(E) | P(D) | P(DE) | P(N) | P(E) | P(D) | P(DE) |
| DAY 1 | $\bar{X}$ | 76 | 79 | 80 | 81 | 74 | 78 | 77 | 79 | 68 | 71 | 72 | 75 | 70 | 74 | 72 | 76 |
| | SD | 10 | 9 | 9 | 9 | 9 | 12 | 10 | 10 | 9 | 10 | 9 | 10 | 9 | 10 | 8 | 11 |
| DAY 2 | $\bar{X}$ | 73 | 75 | 78 | 78 | 69 | 74 | 72 | 75 | 70 | 73 | 76 | 77 | 69 | 74 | 74 | 74 |
| | SD | 10 | 10 | 11 | 9 | 10 | 12 | 10 | 11 | 8 | 9 | 11 | 10 | 8 | 9 | 10 | 10 |
| DAY 3 | $\bar{X}$ | 69 | 72 | 74 | 77 | 70 | 76 | 75 | 77 | 68 | 71 | 74 | 75 | 67 | 72 | 71 | 73 |
| | SD | 9 | 10 | 9 | 11 | 9 | 10 | 10 | 11 | 9 | 9 | 12 | 10 | 9 | 10 | 12 | 9 |

P(N) = program none
P(E) = program extent
P(D) = program direction
P(DE) = program direction and extent

Table 10

Reaction Time Means (msec) and Standard Deviations of
Translation Conditions, Programming Conditions, and Days in Experiment 2

| | | Spatial-Motor Compatible | | | | Spatial-Motor Incompatible | | | | Spatial Transformation | | | | Incompatible-Spatial Transformation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | P(N) | P(E) | P(D) | P(DE) | P(N) | P(E) | P(D) | P(DE) | P(N) | P(E) | P(D) | P(DE) | P(N) | P(E) | P(D) | P(DE) |
| DAY 1 | $\bar{X}$ | 225 | 256 | 261 | 280 | 240 | 326 | 330 | 362 | 219 | 257 | 273 | 287 | 239 | 318 | 334 | 366 |
| | SD | 20 | 27 | 26 | 28 | 21 | 41 | 45 | 40 | 19 | 22 | 27 | 27 | 27 | 32 | 37 | 35 |
| DAY 2 | $\bar{X}$ | 226 | 255 | 262 | 275 | 232 | 313 | 318 | 352 | 221 | 253 | 266 | 284 | 237 | 315 | 325 | 360 |
| | SD | 22 | 25 | 27 | 25 | 26 | 39 | 37 | 38 | 19 | 21 | 28 | 26 | 27 | 31 | 37 | 35 |
| Day 3 | $\bar{X}$ | 221 | 248 | 253 | 267 | 228 | 306 | 304 | 340 | 220 | 251 | 264 | 281 | 232 | 307 | 323 | 354 |
| | SD | 23 | 25 | 26 | 25 | 23 | 33 | 37 | 39 | 20 | 24 | 27 | 25 | 22 | 30 | 34 | 34 |

P(N) = program none
P(E) = program extent
P(D) = program direction
P(DE) = program direction and extent

direction, $F(1,6) = 8.88$, and extent, $F(1,6) = 111.60$. Analysis of programming conditions revealed that MT in the program none condition (70 msec) was faster than program extent (74 msec), program direction (75 msec), and program direction and extent (76 msec), while none of these latter conditions were significantly different. For direction, MT's to the right response keys (69 msec) were faster than to the left response keys (79 msec) and for extent, MT's to the near response keys (58 msec) were faster than to the far response keys (90 msec).

In addition, direction and extent interacted, $F(1,6) = 31.63$, and post hoc inspection showed that MT's were fastest to slowest in the following order: RN(55 msec) < LN(60 msec) < RF(83 msec) < LF (98 msec). Also significant was the translation by direction interaction, $F(3,18) = 3.23$. This interaction resulted primarily because MT's to the right response keys were equivalent in all conditions, whereas, MT's to the left response keys in ST and IST were approximately four to seven msec lower than MT's in SMC and SMI. Since the ST and IST conditions were always presented last, this result suggests that there was some sort of practice effect which differentially influenced movements in the left direction. Finally, the translation conditions, programming conditions, and extent interaction was significant, $F(9,54) = 2.47$, but because no substantive meaning could be discerned from its interpretation post hoc analysis was deemed unnecessary.

Reaction time analyses. The RT means and standard deviations of translation, programming, and days are presented in Table 10. The three-way interaction of translation, programming, and days was non-significant, $F(18,108) = 1.07$, and this result suggested that performance in the translation conditions was not being differentially affected by practice. Therefore, interest focused on the translation by programming interaction, which was significant, $F(9,54) = 33.54$.

Independence of selection and determination -- Analysis of the four compatibility by transformation interaction contrasts again failed to reach significance as shown in Figure 7 and Table 11.

Table 11

Compatibility-Transformation Interaction Contrasts for RT in Experiment 2 (Means in msec)

| | SMC | SMI | ST | IST | $\bar{D}$ |
|---|---|---|---|---|---|
| Program None | (224 - 233) | - | (220 - 236) | = | 1 |
| Program Extent | (253 - 315) | - | (254 - 313) | = | 3 |
| Program Direction | (259 - 317) | - | (268 - 327) | = | 1 |
| Program Direction and Extent | (274 - 352) | - | (284 - 360) | = | 2 |

The set size by compatibility level interaction contrasts, however, yielded somewhat different results (see Figure 8 and Table 12). Of the twelve contrasts, seven were significant. These were: SMC-SMI for extent, SMC-SMI for direction, SMC-IST for extent, SMC-IST for direction, ST-IST for direction, and ST-SMI for direction. All the

Table 12

Set Size - Compatibility Level Interaction Contrasts for RT in Experiment 2 (Means in msec)

| 2 choice P(E) | | | 4 choice P(DE) | | | $\bar{D}$ | 2 choice P(D) | | | 4 choice P(DE) | | | $\bar{D}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SMC | SMI | | SMC | SMI | | | SMC | SMI | | SMC | SMI | | |
| (253 | - 315) | - | (274 | - 352) | = | 16* | (259 | - 317) | - | (274 | - 352) | = | 20* |
| SMC | ST | | SMC | ST | | | SMC | ST | | SMC | ST | | |
| (253 | - 254) | - | (274 | - 284) | = | 9 | (259 | - 268) | - | (274 | - 284) | = | 1 |
| SMC | IST | | SMC | IST | | | SMC | IST | | SMC | IST | | |
| (253 | - 313) | - | (274 | - 360) | = | 26* | (259 | - 327) | - | (274 | - 360) | = | 18* |
| SMI | ST | | SMI | ST | | | SMI | ST | | SMI | ST | | |
| (315 | - 254) | - | (352 | - 284) | = | 7 | (317 | - 268) | - | (352 | - 284) | = | 19* |
| SMI | IST | | SMI | IST | | | SMI | IST | | SMI | IST | | |
| (315 | - 313) | - | (352 | - 360) | = | 6 | (317 | - 327) | - | (352 | - 360) | = | 2 |
| ST | IST | | ST | IST | | | ST | IST | | ST | IST | | |
| (254 | - 313) | - | (284 | - 360) | = | 17* | (268 | - 327) | - | (284 | - 360) | = | 17* |

* $p < .05$

P(E) = program extent, P(D) = program direction, P(DE) = program direction and extent

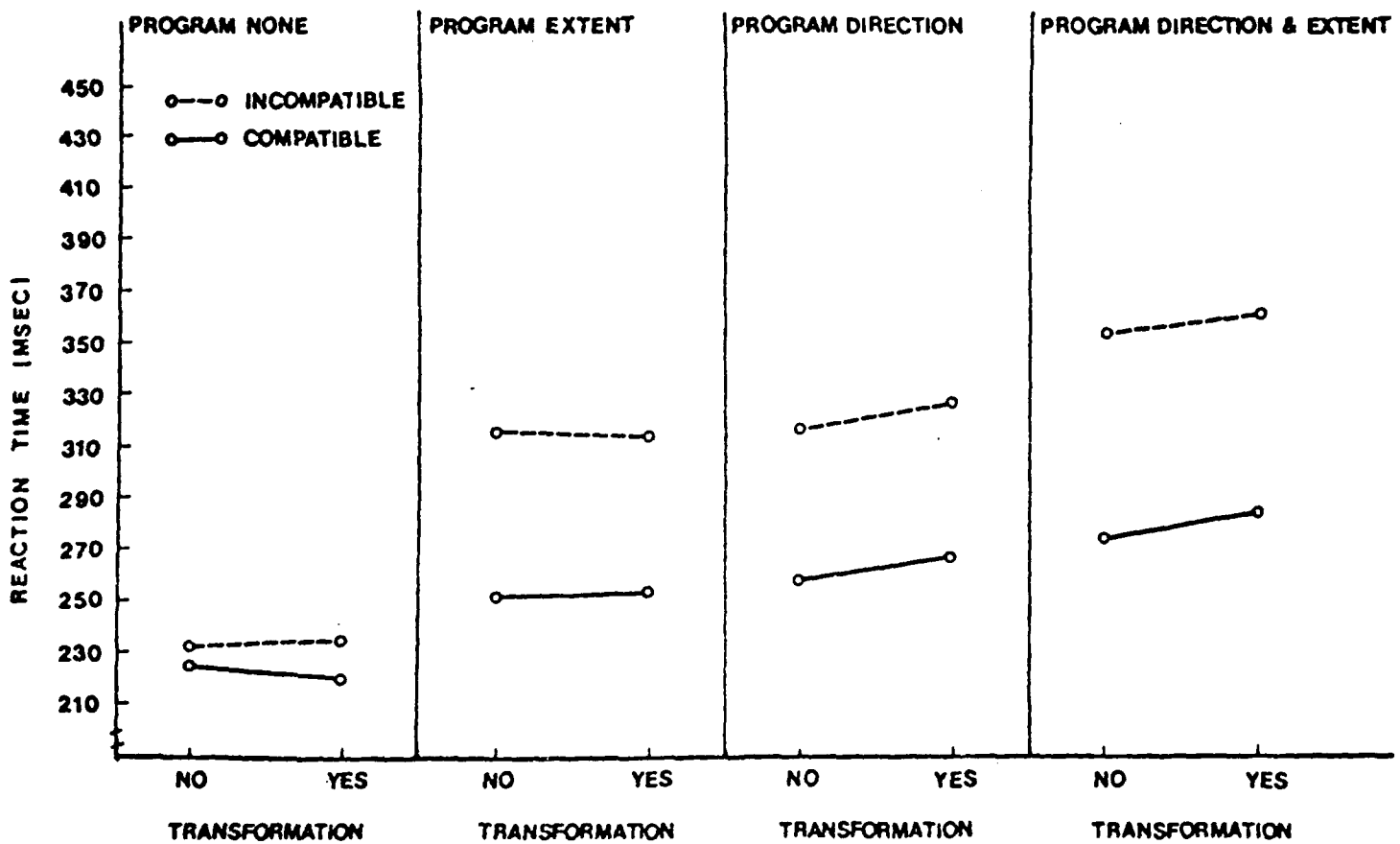



Figure 7. Mean RT (msec) of the compatibility by transformation interaction contrasts within each programming condition.

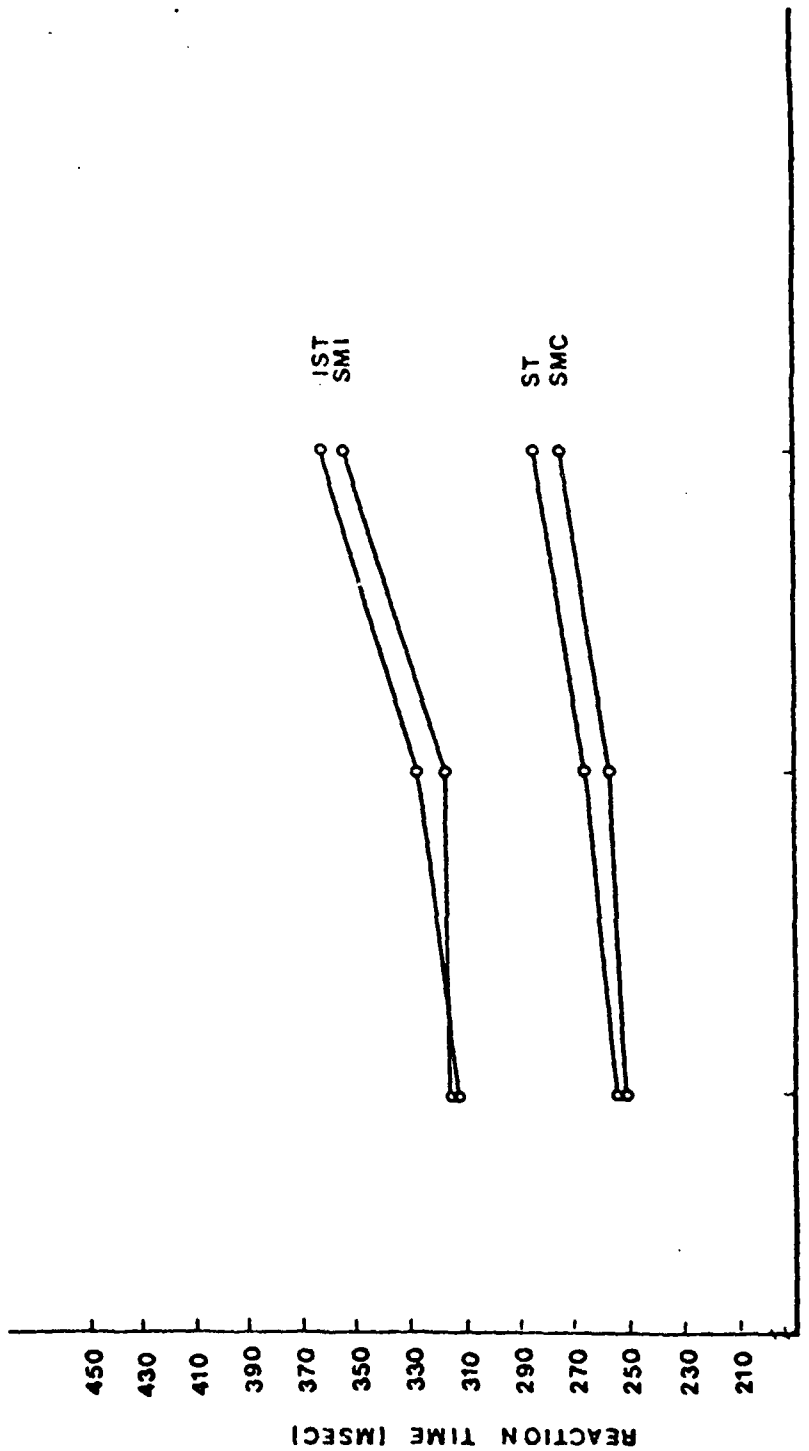



Figure 8. Mean RT (msec) of the set size by compatibility level interaction contrasts.

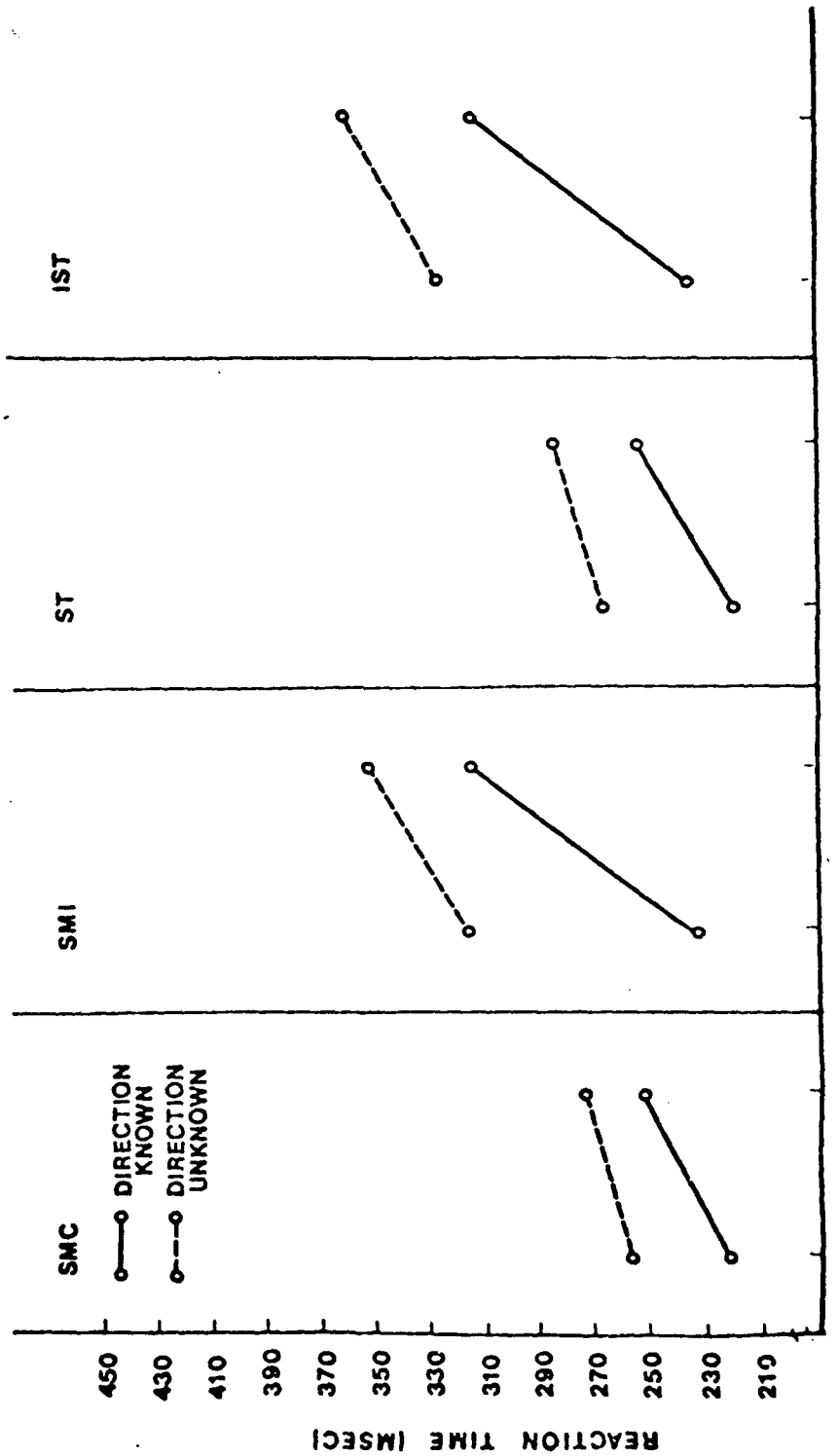



Figure 9. Mean RT (msec) of the four programming conditions within each translation condition.

interactions were over-additive in nature, indicating that these factors affected at least one common processing stage, presumably response determination.

Differential programming -- The simple main effects analysis within each translation condition was significant and Tukey's HSD procedure was used to test for pairwise differences in means (see Figure 9). For SMC, program none (224 msec) had the lowest RT, program extent (253 msec), and program direction (257 msec) had equivalent RT's, and these two were lower than program direction and extent (274 msec). For SMI, the identical pattern of results was found, where program none = 233 msec, program extent = 315 msec, program direction = 317 msec, and program direction and extent = 352 msec. As for ST, program none (220 msec) < program extent (254 msec) < program direction (268 msec) < program direction and extent (284 msec). A similar pattern was evident for IST since program none (236 msec) < program extent (313 msec) < program direction (327 msec) < program direction and extent (360 msec). Comparing these results to Experiment 1, they are indeed very similar, and the only deviation was that program extent is faster than program direction in the ST condition, as well as the IST condition.

Serial versus parallel programming -- The specified interaction contrasts within each translation condition are shown in Figure 9 and Table 13. The outcome of these tests revealed that all interactions were significant in an underadditive fashion.

Table 13

Programming Conditions Interaction Contrasts for RT in Experiment 2 (Means in msec)

| | P(N) | | P(E) | | P(D) | | P(DE) | | $\overline{D}$ |
|---|---|---|---|---|---|---|---|---|---|
| SMC | (224 | - | 253) | - | (259 | - | 274) | = | 14* |
| SMI | (233 | - | 315) | - | (317 | - | 352) | = | 47* |
| ST | (220 | - | 254) | - | (268 | - | 284) | = | 18* |
| IST | (236 | - | 313) | - | (327 | - | 360) | = | 44* |

* $p < .05$

P(N) = program none, P(E) = program extent, P(D) = program direction, P(DE) = program direction and extent

Response selection time analyses. An estimate for selection time ($RS_E$, $RS_D$, $RS_{DE}$) was computed in the manner described earlier and these times are presented in Figure 10. The selection time main effect was significant, $F(2,12) = 51.86$, $p < .05$, and post hoc simple comparisons revealed that $RS_E$ (29 msec) was lower than $RS_D$ (35 msec) and both were significantly lower than $RS_{DE}$ (50 msec). Serial-parallel programming was tested via a complex comparison ($RS_E + RS_D$ versus $RS_{DE}$) and the average of $RS_E$ and $RS_D$ was found to be significantly lower than the $RS_{DE}$ value. Programming conditions also interacted with days, $F(4,24) = 4.77$, and was primarily caused by $RS_{DE}$. Selection time when both direction and extent were unknown was influenced more by practice than were the other two conditions (see Table 15). Differential programming was evident on all three days, as was the underadditive nature of the $RS_E + RS_D$ versus $RS_{DE}$ comparison.

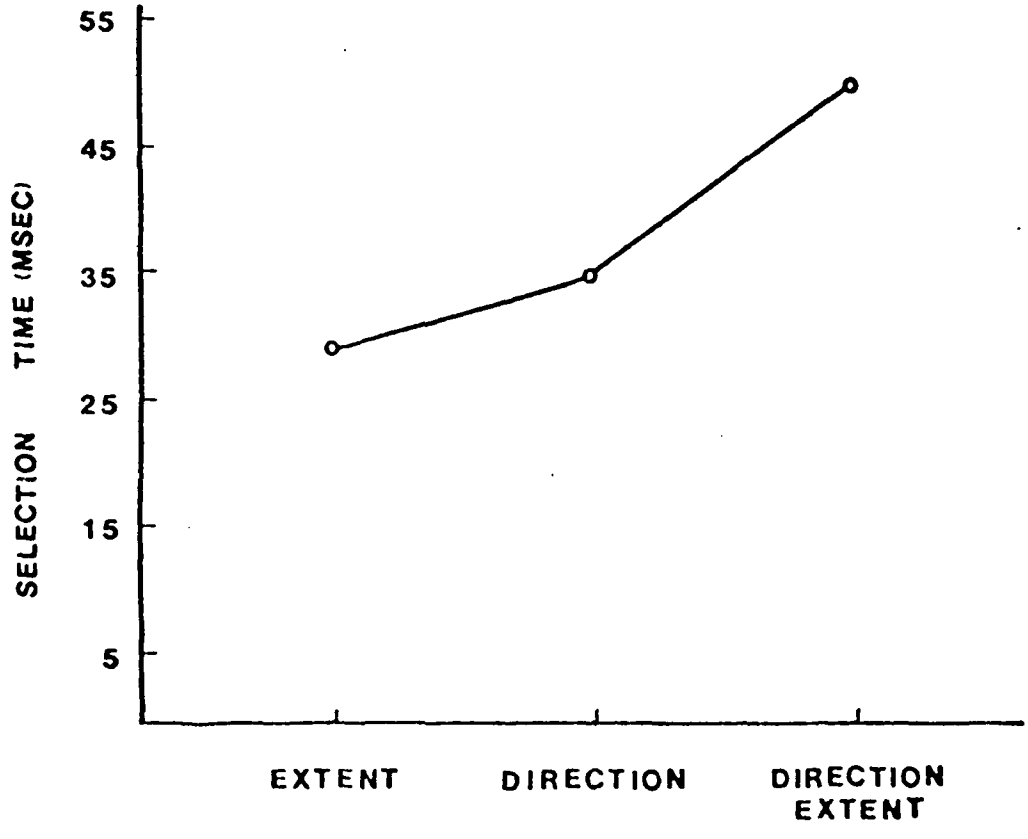



Figure 10. Mean response selection time (msec) of each programming condition.

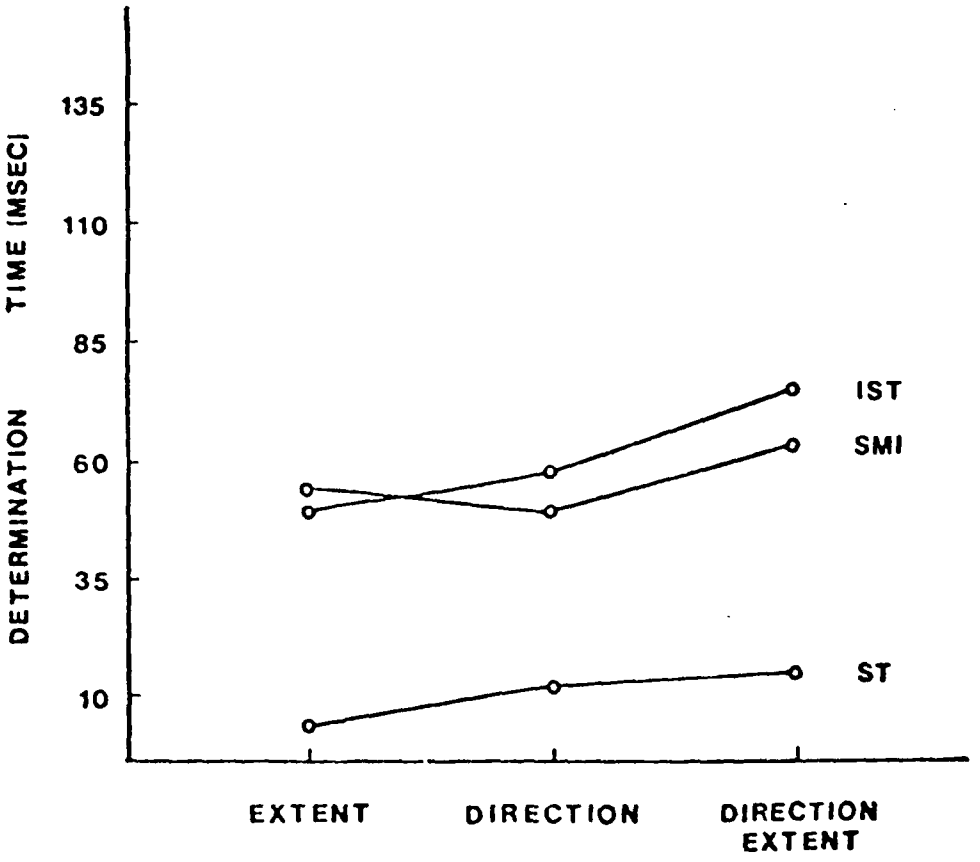



Figure 11. Mean response determination time (msec) of translation and programming conditions.

Response determination time analyses. Response determination times were computed for SMI, ST, and IST, and again within each of these conditions translation times were derived for $RD_E$, $RD_D$, and $RD_{DE}$. The translation by programming conditions interaction was significant, thus permitting a more detailed assessment of the theoretical questions. This interaction is depicted in Figure 11. The independence notion was again tested by a set size by compatibility level interaction, and in three of six instances significance was found (see Table 14). These overadditive interactions were: ST-SMI for direction, ST-IST for extent, and ST-IST for direction. The simple main effects tests within each

Table 14

Set Size - Compatibility Level Interaction Contrasts for Response Determination Time in Experiment 2 (Means in msec)

| 2 choice P(E) | | | 4 choice P(DE) | | | $\overline{D}$ | 2 choice P(D) | | | 4 choice P(DE) | | | $\overline{D}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SMI | - | ST | SMI | - | ST | | SMI | - | ST | SMI | - | ST | |
| (53 | - | 5) | (63 | - | 15) | = 0 | (49 | - | 13) | (63 | - | 15) | = 12* |
| SMI | - | IST | SMI | - | IST | | SMI | - | IST | SMI | - | IST | |
| (53 | - | 49) | (63 | - | 74) | = 7 | (49 | - | 58) | (63 | - | 74) | = 2 |
| ST | - | IST | ST | - | IST | | ST | - | IST | ST | - | IST | |
| ( 5 | - | 49) | (15 | - | 74) | = 15* | (13 | - | 58) | (15 | - | 74) | = 14* |

* $p < .05$

P(E) = program extent, P(D) = program direction, P(DE) = program direction and extent

translation condition were significant and further post hoc analysis revealed that; in SMI, $RD_E$ (53 msec) was equivalent to $RD_D$ (49 msec) and both were significantly faster than $RD_{DE}$ (63 msec), in ST, $RD_E$ (5 msec) was faster than $RD_D$ (13 msec) and $RD_{DE}$ (15 msec), but $RD_D$ and $RD_{DE}$ remained undifferentiated, and in IST, $RD_E$ (48 msec) < $RD_D$ (58 msec) < $RD_{DE}$ (74 msec). Finally. the complex comparisons ($RD_E$ + $RD_D$ versus $RD_{DE}$) were significant for SMI and IST, but not for ST. In the former two instances, the average of $RD_E$ and $RD_D$ was less than $RD_{DE}$, making the comparison underadditive.

The last issue addressed in this experiment was the degree to which selection time and determination time were affected by practice. From Table 15, it was apparent that additional practice had a very minor impact on the speed of the selection process. In fact, comparing Experiment 1, Day 1 to Experiment 2, Day 3, the decreases in selection time for program extent = 6 msec, for program direction = 6 msec, and for program direction and extent = 12 msec. Furthermore, the percentage of CRT accounted for by selection time changed very little across the two experiments.

Again comparing between experiments, the results for determination time were quite different from above (see Table 16). In SMI, average decreases in translation time for program extent = 27 msec, program direction = 27 msec, and program direction and extent = 36 msec. In IST, average decreases in translation time for program extent = 40 msec, for program direction = 50 msec, and for program direction and extent =

Table 15

Mean Response Selection Times (msec) of Experiments and Programming Conditions

| | Experiment 1 | | | Experiment 2 | | |
|---|---|---|---|---|---|---|
| | Extent | Direction | Direction & Extent | Extent | Direction | Direction & Extent |
| $\bar{X}$ | 31 | 35 | 53 | 29 | 35 | 50 |
| * % | 12.05 | 13.34 | 18.57 | 11.46 | 13.39 | 18.23 |

* Refers to percentage of choice reaction time associated with response selection

Table 16

Mean Response Determination Times (msec) of Experiments, Translation Conditions, and Programming Conditions

| | | Experiment 1 | | | Experiment 2 | | |
|---|---|---|---|---|---|---|---|
| | | Extent | Direction | Direction & Extent | Extent | Direction | Direction & Extent |
| Spatial-Motor Incompatible | $\bar{X}$ | 80 | 76 | 99 | 53 | 49 | 63 |
| | *% | 23.00 | 21.78 | 25.40 | 16.83 | 15.46 | 17.90 |
| Spatial Transformation | $\bar{X}$ | 15 | 21 | 38 | 5 | 13 | 15 |
| | *% | 5.54 | 7.45 | 12.03 | 1.97 | 4.85 | 5.28 |
| Incompatible Spatial Transformation | $\bar{X}$ | 89 | 116 | 137 | 49 | 57 | 74 |
| | *% | 24.59 | 29.44 | 31.71 | 15.65 | 17.74 | 20.56 |

* Refers to percentage of choice reaction time associated with response determination

63 msec. In ST, average decreases for extent = 10 msec, for program direction = 8 msec, and for program direction and extent = 23 msec. The percentage of CRT accounted for by determination time was also directly related to the size of these estimates, as well as the magnitude of the observed decreases. When the translation was more difficult (more time consuming) it benefited most from practice (SMI and IST) and when the translation was easy to begin with (less time consuming) it benefited least from practice (ST).

Discussion

Since differential practice effects were apparent in the initial experiment the data were deemed unreliable. In an attempt to alleviate this extraneous source of variance, this second experiment replicated the first using the same subjects. It was hoped that the differential effect would be eliminated with additional experience, and thereby, provide a more reliable indicant of the processing operations being studied. The lack of a significant translation conditions, programming conditions, and days interaction indicated the experiment was successful in this regard. In fact, eliminating the differential effect seemed to markedly change the outcome of the experiment.

One result that was not different across experiments was the lack of a compatibility-transformation interaction. In fact, the seriality was even more pronounced than in the initial experiment. The IST condition appears to be most responsible for this effect since its RT decreased to the point of being nearly equivalent to the SMI

condition. It seems that the most reasonable explanation for this occurrence is the ease with which the spatial transformation could be performed, as evidenced by the ST condition. Therefore, this component probably added very little to task complexity in the IST condition, and given this fact IST and SMI RT's should be very similar. Such results do suggest that the compatibility and transformation manipulations may not be useful in combination when one is attempting to isolate the response determination processing stage; at least for a relatively easy spatial transformation like that in the ST condition.

Although the compatibility-transformation interaction contrasts remained non-significant, the set size-compatibility level interaction contrasts were more encouraging. For the most part, SMI and IST interacted with the SMC and ST, indicating that the conditions requiring the greatest amount of translation were also affected the most by increases in set size. The overadditive nature of these contrasts does indeed support the view that determination is a legitimate stage, independent from response selection. Also, these contrasts were significant for both programming extent and programming direction, suggesting that both parameters were being programmed prior to response initiation. Further evidence for the separation of determination and selection was garnered from response determination time, in which set size and compatibility level again interacted. The pattern of interaction was such that determination time for IST (both direction and extent) and SMI (only direction) was more sensitive to increases in

set size when contrasted with ST. Collectively, then, the findings for PT and determination time provide converging evidence that response determination is an independent stage and that the effects of stimulus-response translations are localized in this stage.

Recall that Rosenbaum (in press) reported differential RT effects among the movement parameters of arm, direction, and extent whereas Goodman and Kelso (Note 4) failed to replicate these results. The principle difference between these two investigations was the nature of the stimulus-response mappings: in the former, mappings were indirect and in the latter, mappings were very direct or compatible. A post hoc, but logical, interpretation of these findings is that the presence of a translation induces differential RT's, and the absence of a translation eliminates differential RT's.

The present investigation sought to test this hypothesis by including tasks that varied in the type and degree of translation required. In the direct mapping condition (SMC), overall RT in the program extent and program direction conditions was equivalent. In contrast, two of the three translation conditions (ST and IST) showed that RT for extent was faster than RT for direction. These findings, then, have replicated both the Rosenbaum (in press) and Goodman and Kelso (Note 4) data, and they strongly suggest that differential RT's are associated with the need to perform some translation process. The estimates of response determination time were also complimentary to the above conclusion. In the ST and IST conditions, the translation

time for extent was less than for direction. An unexpected result, however, occurred in the response selection time analysis. The selection time of extent (29 msec) was significantly different from the selection time of direction (35 msec), indicating that some of the differential RT effect must be attributed to the response selection stage.

On the surface this finding appears to be support in Rosenbaum's (in press) favor, since it suggests that some of his observed RT differences could have been response programming in nature. Such a finding, however, fails to totally negate the importance associated with the evidence substantiating the experimental hypotheses. This statement is made for two reasons. First, the differential effect was evident only after an extreme amount of practice. An amount considerably greater than that received by Rosenbaum's subjects. By the end of Experiment 2 subjects had experienced nearly 12,000 trials, whereas, Rosenbaum's subjects only experienced 768 trials. Moreover, for the IST group in Experiment 1, where significant differential effects were found, the difference was localized in determination time, and when compared to selection time, the largest percentage of CRT was also in determination time. Given the practice level in the Rosenbaum experiment, the IST data would seem to indicate his differences were most likely caused by the required translation. Second, the magnitude of the differential RT effect between extent and direction in the Rosenbaum study appeared to be much larger than the

differences obtained in selection time in the present experiment. Therefore, the most reasonable interpretation seems to be that Rosenbaum's results reflect non-motoric processing operations, and forces one to argue against the claim that his findings represent only response programming operations underlying the construction of MP's. Although one must conclude from the above findings that differential programming and differential processing occurs in response selection and response determination, respectively, the more significant and prominent effects were caused by response determination.

One disturbing aspect of the RT and determination data was the lack of a differential effect in the SMI condition. What makes this result puzzling is that the translation appeared to be almost as difficult as in the IST condition, where the differential effect was found. Furthermore, the translation in the ST condition was considerably easier, yet it too showed the differential effect. Thus, it seems that difficulty of translation is not a factor entering into the differential programming or processing effect. The only obvious difference between the groups that showed the effect (ST and IST) and those that did not (SMC and SMI) was the "go" light configuration. Perhaps these results indicate that the spatial framework of the visual display plays a role in creating the differences. Unfortunately, the reasons or mechanisms behind such an explanation are unclear at this point.

At this point it will be useful to dispell one potential criticism of the results in Experiment 2. It is rather obvious that many of the differences in means found to be significant in this second experiment are no larger than the differences found to be non-significant in the initial experiment. If fact, some are even smaller. Given these circumstances, one might argue that the significant effects in this latter experiment are merely a statistical artifact. Such an argument, however, is more imagined than real. In tasks such as those used in the present investigation both overall RT and variability in RT decreases with extended practice. As a consequence, group means become more similar (resulting in reduced mean differences) and at the same time estimates of error become smaller. Comparing experiments, these characteristics are clearly identified in the translation and programming conditions means and standard deviations, and also in the estimates of mean square error. The end result is ultimately greater statistical power in detecting smaller differences as being significant. Thus, one would expect smaller effect sizes to be more important and meaningful with well-trained individuals.

Comparison of selection and determination time across the two experiments further implicates the dominance of the translation process when stimulus-response mappings are less than optimal. Comparing across experiments, the selection times for each programming condition were virtually identical, as were the percentages of CRT attributed to response selection. Thus, within the constraints of the present

investigation, the programming times of extent and direction are insensitive to practice. One qualification that must be made, however, is that each subject received five to eight practice sessions in the SMC condition prior to the start of the experimental phase of the investigation. It may be that during these sessions programming times decreased and achieved an asymptotic level, but was masked as a floor effect in the latter sessions.

Teichner and Krebs (1974) argued that the locus of RT reductions in tasks requiring a stimulus-response translation is in the efficiency with which the translation can be completed. Further, they maintained that the more difficult the translation, the more likely it will be favorably influenced by practice. From the RT data, the most difficult translation was in the IST condition, followed by the SMC and ST conditions. This same leveling was also found in the estimates of translation time. Moreover, decreases in determination time across experiments were much larger than in selection time, at least for SMI and IST. The small contribution of determination time to overall RT in the ST condition also provides some indication that when the translation is relatively easy and well practiced, it can nearly be eliminated. Thus, Teichner and Kreb's (1974) speculations are fully supported.

With respect to the serial-parallel programming issue, RT in all four translation conditions supported a parallel programming interpretation: when unknown prior to the "go" signal, the programming of direction and extent was accomplished simultaneously. Further, these

results are generally consistent with those in Experiment 1. It should be noted that this evidence contrasts with the serial programming conclusion reached by Rosenbaum (in press). The present data, however, are not the first to oppose Rosenbaum's interpretation. For the programming of direction and extent, Kerr (1976) reported findings that support parallelism. Although much of Kerr's data suffers from problems with speed-accuracy trade-off, in instances where this problem was not apparent RT showed an underadditive pattern, and thus, parallel programming.

For the most part, the response selection time and response determination time finding also supported a parallel programming view. In both experiments, selection time and the SMI and IST conditions for determination time were indicative of parallel programming. In fact, the only part of the data that gave no indication whatsoever for parallelism was determination time in the ST condition. This result clearly conflicts with those of the SMI and IST conditions and implies that translation difficulty has some effect on the nature of the processing within the response determination stage. When the translation is relatively easy, and extent and direction are uncertain prior to response initiation, the individual translations are done serially. In contrast, when the translation is difficult and time-consuming, and extent and direction are uncertain, the necessary translations are completed simultaneously.

In summary, a reasonable amount of support was generated for the two principle experimental hypotheses. To substantiate the criticisms posited against Rosenbaum (in press), it was first necessary to demonstrate that stimulus-response translations were localized in a stage other than response selection. This evidence was found in the over-additive nature of the set size-compatibility level interaction contrasts, and these results agree with previous findings that have shown a similar interaction (Smith, 1979; Theois, 1975). With regard to differential programming, the presence or absence of a translation was the explanation offered to account for the discrepancy between Rosenbaum and Goodman and Kelso. Again, the data revealed that such an interpretation provides an accurate account of the reported differences. However, there was some indication that differential programming can occur in response selection, but only after considerable practice, and not all translations result in differential processing. Compared to selection time, determination time was longer, accounted for a larger percentage of CRT, and was influenced more by practice. Finally, in most instances, parallel processing and programming of extent and direction was found; yet another result that conflicts with Rosenbaum's data.

## GENERAL DISCUSSION

One of the primary objectives of response programming research is to identify the underlying structure and composition of the MP. With this purpose in mind, a number of investigators have attempted to define the relationships among various movement parameters (e.g. arm, direction, extent, duration) thought to be involved in the construction of MP's. Recently, Rosenbaum (in press) has introduced a variation of the partial advance information paradigm (Leonard, 1958) as another method for assessing the response programming that necessarily precedes response initiation. In Rosenbaum's view, the utility and explicit purpose of the movement precuing technique (as he termed it) is to "shed light on the construction of motor programs after non-motoric decisions have been made" (p. 2). The assertion in the present investigation, however, is that Rosenbaum failed in his stated purpose; to assess only motoric operations. The problem lies not in the partial advance information nature of the precuing technique, but rather Rosenbaum's conception of it. More specifically, the experimental task designed by Rosenbaum inextricably confounded measures of both non-motoric and motoric processing operations, and as such necessarily forces a re-examination of his conclusions regarding MP construction.

Such a criticism is made because of the indirect nature of the

mappings between stimuli and responses in the Rosenbaum (in press) study. When a reaction stimulus and its associated response have a straightforward or highly compatible relationship, RT within the precuing framework would certainly reflect just motoric operations. However, in instances when these same mappings are indirect and relatively unpracticed, non-motor, cognitive decisions (what has been termed stimulus-response translations) make an unavoidable and significant contribution to RT (Teichner & Krebs, 1974). Unfortunately for Rosenbaum, the use of colored dots as "go" signals places him in this latter category. The specific intent of the present study, therefore, was to demonstrate that stimulus-response translations are localized in a processing stage usually not associated with motoric processing operations (Kerr, 1978) and to illustrate that the presence of these translations is the factor most responsible for Rosenbaum's findings. From a HIP point of view, translations are said to occur in a processing stage called response determination (Theios, 1975) and motoric programming operations are said to occur in a processing stage called response selection (Kerr, 1978).

The results of Experiment 1 clearly failed to provide strong support for either of the experimental hypotheses stated above. A detailed inspection of the data, however, showed that a differential practice was a significant confounding variable, and it was concluded that this factor was either partially or totally responsible for an inadequate test of the above hypotheses. In Experiment 2, an attempt

was made to eliminate this differential effect, primarily found in the SMI, ST, and IST conditions, by re-testing the same subjects in a replication of the initial experiment. The results revealed that the experiment was successful in this regard, and in addition, considerable support was found for the experimental hypotheses. Response determination was indeed shown to be an independent processing stage and the presence or absence of a translation predicted whether Rosenbaum's results would be replicated. Although the intent of the reported experiments was to determine if Rosenbaum's effects were truly response programming in nature, the outcome of these experiments has several important implications for the response programming area in general. Before these implications are discussed, however, it will be enlightening to consider other response programming experiments whose results have direct bearing on the distinction between determination and selection.

In another recently completed doctoral dissertation, McCracken (1979) provided converging evidence for the separation of the response determination and response selection stages. In fact, these results illustrate a very interesting relationship between the two stages. In a somewhat different experimental task, but using the precuing technique, McCracken examined the programming characteristics of movement duration (150 msec, ± 30% and 400 msec, ± 30%), extent (near and far), and direction (left and right). Each subject's task was to move at one of the designated movement durations and strike one of

four movement barriers situated in the frontal plane. Precues were given verbally and two colored lights (red and green), mounted at the base of each barrier, served as "go" signals. The desired movement duration was cued by one of the colored lights (e.g. red = 150 msec and green = 400 msec), while extent and direction information was directly discernible once the reaction stimulus was illuminated. Thus, an experimental situation was created in which two parameters (direction and extent) were highly compatible, but the third (deviation) definitely required a stimulus-response translation.

As expected, the number of parameters remaining to be programmed had a significant effect on overall RT. As before, however, the data of most interest was the partial pre-programming conditions. Within the program one parameter conditions a differential RT effect was found, where program duration was longest, program extent was shorter, and program direction was shortest. As for the program two parameter conditions, the programming of direction and extent was fastest and the programming of duration and extent and duration and direction were slower, but equivalent to each other.

When compared to Rosenbaum (in press), at least two major differences are apparent. First, Rosenbaum reported that programming time for direction was longer than programming time for extent, whereas, McCracken (1979) reported a longer latency for programming extent. Second, Rosenbaum found that the hierarchical effect in the

program one parameter conditions also held in the program two parameter conditions. That is, the time to program arm and direction was longest, program arm and extent was shorter, and program direction and extent was shortest. In contrast, the same pattern was not evident in McCracken's study. The time to program duration and extent was equivalent to the time to program duration and direction.

McCracken (1979) argued that the reversal between extent and direction had to be interpreted in light of their importance in defining movement duration. More specifically, before duration can be fully programmed, it is necessary to have some knowledge about movement extent. In contrast, direction information provides little additional knowledge that will facilitate the programming of duration. Hence, extent maintains a more important relationship with duration than does direction, and when extent is unknown prior to response initiation a longer RT latency will result.

For the purposes of the present discussion, however, the outcome of the program two parameter conditions is a more provocative finding. If Rosenbaum's hierarchical pattern of results had have held in McCracken's experiment the time to program duration and extent should have been longer than the time to program duration and direction. What does the lack of this difference imply? Three plausible explanations seem reasonable. First, after the duration translation was completed the two movement parameters were programmed in parallel. Second, the programming of the compatible parameter was completed

during the translation of the duration parameter. Finally, some combination of temporal overlap and parallel programming of the two parameters occurred. Based on the parallel programming relationship that direction and extent had in response selection time of the present experiments, it is conceivable that when paired with duration any remaining unknown parameters are programmed simultaneously. The second and third alternatives are, perhaps, more provoking because they suggest a certain degree of temporal overlap between determination and selection. In other words, these stages of processing are performing their respective operations in parallel. Although Sternberg (1969) argues that one of the fundamental assumptions of additive factor methodology is the seriality of processing stages, the most parsimonious account of McCracken's data favors a temporal overlap notion, and as Taylor (1976) points out, there is nothing sacred about the seriality assumption. Moreover, Stanovich and Pachella (1977) assert that the idea of overlapping stages increases the predictive power of the additive factor method. Such issues are certainly ones for future research to consider and it would seem that a properly designed series of experiments could easily test them.

Rosenbaum (in press) and McCracken (1979) are not the only investigators who have failed to recognize the distinctive processing operations of determination and selection, and as a consequence have confounded their results with these two stages. Megaw (1972), Klapp (1977), Klapp and Erwin (1976; Expt. 3), Klapp and Wyatt (1976),

and Klapp, Wyatt, and Lingo (1974) are subject to the same criticism. Megaw's experimental arrangement was described earlier and it was pointed out that the movement task created a situation where extent was spatially motor compatible, but direction was spatially motor incompatible. He found that RT was longer when direction was uncertain, and on this basis concluded that it took longer to program direction than it did to program extent. However, since RT for direction was a measure of both translation and programming time such a conclusion is invalid. Further inspection of Megaw's data reveals additional support for the arguments being developed in the present investigation. When he compared the time to program direction with the time to program direction and extent no differences in RT were apparent. This result can be explained within the present framework in one of two ways. Either the programming of extent and direction was done in parallel or there was some temporal overlap of the translation and programming operations.

In a series of experiments on the response programming of duration, Klapp (1977), Klapp and Wyatt (1976), and Klapp, Wyatt, and Lingo (1974) have utilized a morse code key task involving either a dah (hold) or a dit (release) response. For the hold movement, subjects were required to depress and hold down the key, and then after some specified length of time to release. For the release movement, subjects were required to simply depress and release the key as quickly as possible. In each study, RT for the hold movement

was longer than the release movement. Klapp and his colleagues have interpreted this result to mean that the hold movement is more complex because of its timing component and thus takes more time to program. Inspection of the method of cuing responses, however, shows that reaction signals were either colored lights or rows of lights that had been arbitrarily designated to indicate a dit or dah response. Here again, such tasks introduce and necessitate a translation, thereby confounding cognitive and motor processing operations. Rather than the programming of the hold movement taking longer than the programming of the release movement, the differential time could be localized in the translation times of these two responses, but one is unable to isolate its locus because the two stages are confounded.

It would seem that in any of these experiments where the duration parameter was the only one being manipulated a test of the confounding notion could be done very easily and would simply involve a Donder's type C reaction. In blocked trials, subjects would be instructed to respond only if a colored light represented a prespecified duration and not to respond if a colored light represented the unspecified duration. Since response selection time is assumed to be minimal in such a task, it might provide a good index of the length of the translation times for the movement duration parameter and whether these times differ from each other.

Providing one agrees with the foregoing arguments, it soon becomes apparent that the experimental manipulation of certain movement

parameters will almost always confound the determination and selection stages. The most obvious parameter is that of duration. With the parameters of arm, direction, and extent, it is easy to design a spatially motor compatible task where the mapping between stimuli and responses is direct, and thus enabling the study of just response programming operations. Within the limitations of the current methods of studying response programming, however, it is difficult to envisage an experimental setup in which the mapping for duration is direct. Consequently, translation and programming will be confounded components in the reaction latency. Perhaps the only way to alleviate this problem is by giving extreme amounts of practice in performing the task. In Experiment 2, there was some indication that translation times were considerably reduced with practice. In fact, the spatial translation in the ST group was nearly eliminated with practice. The real question though is how much practice will be necessary for the same to happen with duration. After all, the translation in the ST group was rather easy, yet it took an extremely large number of trials to reach the level it did.

Based on the precuing studies completed to date, some preliminary characteristics of the response determination and response selection stages can be identified. The processing within the response determination stage is an interesting one because it seems to display a certain degree of flexibility which is in some way related to translation difficulty. That is, the difficulty of the translation

to be performed determines whether the processing is done in a serial or parallel fashion. When translations demand considerable time, they are processed simultaneously, but when translations are relatively simple or easy, they are processed serially. Thus, the response determination stage has some adaptability in the type of processing it can perform, as well as flexibility in determining the most efficient processing mode. Practice is another variable that has a significant influence on the determination stage; the time to complete difficult translations decreases dramatically with practice. Probably the question of most interest is whether translations can be completely eliminated with sufficient practice. As stated earlier, there was some indication that a simple spatial transformation was almost eliminated with extreme practice.

The internal processing of response selection can be characterized as being parallel; at least for the programming of arm, direction, and extent. Further, this conclusion applies to inexperienced subjects (Goodman & Kelso, Note 4) and highly trained subjects (present investigation). Although Rosenbaum (in press) favored a serial interpretation of his data, the locus of that effect can only be ascertained after the same subjects have performed a spatially motor compatible task as well as his translation task. The actual programming time of movement duration and its relationship with other movement parameters has yet to be isolated in a single experiment, thus no conclusion about duration is possible at this time.

Perhaps the most interesting relationship is seen when one considers the possible interactive nature of determination and selection. McCracken's (1979) findings in the partial pre-programming conditions suggest that the operations of these two stages can overlap in time, meaning that while the translation for one parameter is in progress, the programming of a second parameter, not requiring a translation, can also be done at the same time. Realizing the usual reservations about advocating post hoc interpretations, an experiment that addresses this issue on an a priori basis is now needed. If support can be generated for the temporal overlap hypothesis, it will point out a temporal relationship between determination and selection that will be difficult for future response programming theorizing to ignore.

In conclusion, one of the most revealing aspects of this study has been the demonstration that several investigators have violated an assumption basic to response programming. This is the notion that CRT isolates and measures motoric processing operations after all other cognitive decisions have been completed. It was shown that cognitive decisions (stimulus-response translations) are necessarily introduced whenever stimulus-response mappings are indirect. It was further demonstrated that the locus of these translations was in a processing stage not usually reserved for programming operations (Kerr, 1978). Moreover, it was pointed out that certain movement parameters (e.g. duration) and experimental manipulations (e.g.spatial

motor incompatibility) induce these intermediate translations. Therefore, if such instances are to be of continued interest within a response programming framework one of two choices must be made: either response programming experiments must be designed to preclude the cognitive component, or the contemporary view of response programming must be re-formulated to consider response organization processes that encompass both cognitive and motor processing operations. The latter course seems to be the more judicious since it will promote and encourage a variety of theoretical issues concerning MP construction that might otherwise be ignored.

The second alternative seems preferable from a practical viewpoint, also. Given that humans, in any instance in which they are required to not only process information from some machine (be it computer, airplane instrumentation panel or tracking device) but to also physically respond on the basis of that information, seek to perform rapidly and without error it seems extremely appropriate that recognition of both cognitive and motor processes be maintained. From this research it is apparent, for example, that requiring the operator to translate somewhat abstract informational stimuli to overt actions can significantly increase the latency of the motor response. It is more advantageous to give the stimuli and the desired response greater compatability in order to ensure that unnecessary cognitive activity is avoided, and to lessen the large costs, in time, personnel, and money, that extensive practice under noncompatible stimulus-response conditions seems to require.

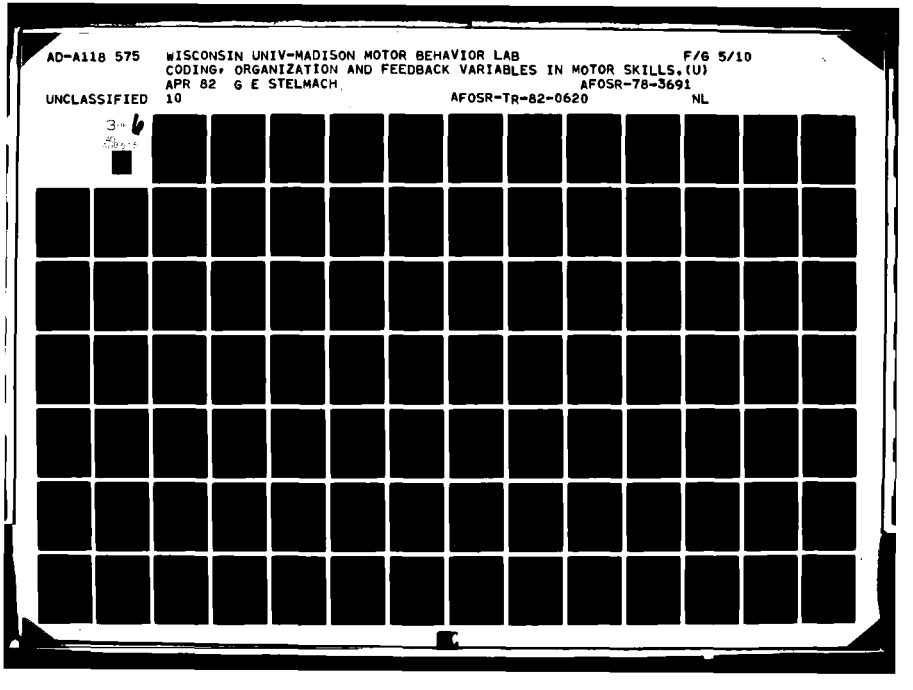
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# Bimanual Movements: The Influence of Direction Changes on Coordination

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Introduction

In no aspect of science pledging paradigmatic allegiance to experimental psychology are the consequences of our reductionistic approaches resounding more clearly than in motor behavior. It has become increasingly apparent that the 'facts' one learns from studying, for instance, discrete single limb responses to discrete single-instance stimuli have, at best, only a limited influence on our understanding -- real or potential -- of the organization of complex purposive acts. Specifically, in attempting to understand the bases of process and function, scientists have often examined very simple acts, and in doing so have perhaps pursued the notion that single limb movements need to be understood before complex multiple-limb activities can be addressed, or that on the basis of single limb truisms, bimanual characteristics can be deduced. Recent evidence on bimanual movements, as equivocal as it may be on a finer experimental level, has clearly and undeniably revealed that the principles associated with single limb movements are not at all easily transferred to two-handed movements, even those occurring in similar experimental settings.

The desire to accelerate the trend away from such limited and, for all intents and purposes, inapplicable experimentation to that with some ecological validity provided the broader of this experiment's basic purposes. At a more detailed level, it was hoped that two recently proposed modes of bimanual coordination could be distinguished experimentally.

In order to fully recognize the impact of traditional research's retardation of the examination of ecologically valid behaviors, and in

particular, of bimanual movements, it is worthwhile to review the few scattered pockets of data.

Early Research on Bimanual Acts

The behavioral and neuroscientific areas of research have produced very few accounts of bimanual coordination control characteristics although interest has been expressed, on odd occasions, from as far back as the beginning of this century (Woodworth, 1899). The first serious, scientific address of bimanual coordination began in the 1960s and it included Air Force-sponsored research (e.g., bimanually operated navigation equipment. The earliest research was essentiall grounded in attempts to see if (not how) humans could perform bimanual movements. Simultaneously, Paillard (1949), Warrick and Turner (1963), and Bartlett and White (1965) all found that, indeed, a high degree of temporal synchrony was possible. Norrie (1964), however, in using gross motor responses, found that despite urgings to perform simultaneously, subjects could not do so. The greater the task dissimilarity between each limb, the greater the difference in reaction time (RT), she found.

Much, if not all, of this work was undertaken atheoretically, but in 1965, Peterson did an experiment similar to Norrie's (1964) and concluded that, in terms of the response-response (R-R) compatibility notion effects arise whenever two or more separate responses are carried on concurrently. The data, like Norrie's (1964, 1967), revealed distinct interactions of performance across hands: in Peterson's terms, "the level of performance of one hand (executing one response) depended upon the nature of the response made with the other hand" (1965, p. 236). These studies proved to be accurate forecasters of both the data and debate that has arisen recently.

Contemporary Research of Bimanual Movements

One of the first to address bimanual interactions theoretically was Cohen (1970, 1971) who noted that since, with the exception of Norrie (1964) and Peterson (1965), only mirror-image movements using homologous muscle groups had been examined, acceptance of any general control conception on the basis of such movements could be misleading. Cohen's experiments were planned to determine the locus or loci of the noted interference between the limbs; that is, whether the interactive effects occurred as a result of competing motor commands or as a result of competing afferent information.

Cohen (1970) found that alternating flexion and extension movements in the ipsilateral limb were modified by action of the other limb. These modifications which occurred immediately after contralateral action was initiated included a momentary halt in ipsilateral limb activity, a change in the rate of ipsilateral alternation, or a premature reversal in the direction of the alternating movement. Never was an unbroken rhythm of alternation found in the ipsilateral limb, and resumption of the alternation was almost always out of phase with the initial rate. Passive movements of the contralateral limb did not affect the pattern of alternation in the active limb, even when the subject was forced to attend to it by counting the number of passive movements, and nor were any effects apparent when the ipsilateral limb exerted a constant isometric torque.

Interpreting these results, Cohen (1970) posited that the primary cause of the interference is an overload upon the "central signal processing mechanism" (p. 271) which, in turn, causes a

reduction in the generation of motor commands to the moving limb. The role of such a regulatory mechanism, Cohen proposed, is to reduce the effect of competing afferent signals from the two limbs, and its operation could be seen to be manifested in the disruption of the pattern in the moving limb to the extent that it becomes synchronous with the contralateral pattern; the mechanism attempts to make redundant one set of afferent signals by making them the same as the other set. Subsequent data (Cohen, 1971) indicated that the precision and speed with which bimanual movement sequences can be generated depends on the muscle groups involved. While his earlier afferent overload hypothesis can be supported by these data (synchronous mirror-image movements effectively generate the same peripheral information from each limb, thereby requiring the monitoring of only one set of information), it does not necessarily rule out the possibility of efferent interference occurring during its transmission from each hemisphere. Preilowski (1975) challenged Cohen's position on the basis of evidence generated by experiments with partial and complete "split-brain" patients. Rather than accepting a capacity - based model of bimanual interaction, Preilowski (1975) hypothesized that the noticeable interactions were the result of efferent interactions, and that they occurred at subcortical levels; a suggestion which has other support (Brinkman & Kuypers, 1972), but one which Cohen (1970) either did not consider or rejected. Preilowski's model (1975), which has been used by others to explain data (e.g., Marteniuk & MacKenzie, 1980; MacKenzie & Marteniuk, 1981), postulates that for mirror-image movements (to be performed at the same degree of intensity), the efferent commands match each other, and although they interact bilaterally during their transmission, they do not interfere with each other. However, if the parameters for the movement are different for each limb, interference would occur at the points of

bilateral interactions (which may extend, it is argued, as far down as the spinal level).

Recent evidence of Kelso, Southard and Goodman (1979a, 1979b) provides ground for rejecting Cohen's (1971) contention that motor commands for each limb are generated independently with a transcollosal (cortical) interaction linking mirror-image movements. Three experiments, employing the same paradigm, but altering the direction of movement in each experiment, consistently revealed that when two hands are required to make simultaneous, but not necessarily equidistant movements, the hands begin moving at the same time and also strike the designated targets simultaneously. The data also revealed that the hand moving to the difficult target "dictated" to the other hand the movement time, that is, the "easy" hand slowed down to pair itself with the difficult hand; and not only did the "easy" hand elongate its response time, but it did so without disruption to its own kinematic pattern. It did not arrive at its target and then wait for the other hand to catch up (as Norrie's, 1964, data indicate it can in more complex tasks); rather, it followed a different velocity, acceleration (and, obviously, displacement) pattern but in the same time frame as the other hand.

Subsequent evidence (Marteniuk & MacKenzie, 1980) has strongly challenged the view that, in bimanual acts, the two limbs are constrained to act as one unit. In an experiment with a very similar paradigm, Marteniuk and MacKenzie failed to support the Kelso, et al. finding that in bimanual movements response time increases only in the hand moving the shorter distance; Marteniuk and MacKenzie found also the reciprocal effect where the response time

for, say, the left hand in the difficult-difficult conditions decreases when paired in a difficult-easy conditions. It might be remembered that Norrie (first in 1964 and more clearly in 1967) and Peterson (1965) also found such interactions, although they did not choose to interpret them within any theoretical context. Preilowski (1975) did interpret his (similar) findings, and proposed that the commands originating from each hemisphere interact -- by way of a sort of neural 'crosstalk' --- at one or more locations to produce interference in the contralateral limb. Subsequent data collection (Marteniuk et al., Note 1) and interpretations (MacKenzie & Marteniuk, 1981; Marteniuk, 1981) have also led to the conclusion that, while incapable of dismissing coordinative structures (Kelso et al., 1979a) as a control phenomena, the evidence does not "support the notion that coordinative structures lie latent in the CNS, ready for immediate use" (Marteniuk & MacKenzie, 1981, p. 184).

A conclusion to the review of the sparsely distributed body of literature on bimanual coordination might be just as well concluded by recognizing that all the evidence that has examined both symmetrical and assymmetrical movements revealed distinct interaction effects. That such interference across limbs occurs exists, there can be little doubt. However, it is the precise nature of the interactions which is cause for theoretical consideration and the impetus for this experiment. Rather than using a button-pushing task, a track is used, and rather than varying movement amplitude movement directions vary for the hands.

Specific questions and hypotheses about the issues can be addressed in terms of each of the dependent variables used; reaction time and

movement time. In general terms firstly, support for the coordinative structure interpretation of Kelso et al. (1979b) would come from data which show that the two hands are initiated and terminate movements together, regardless of whether the task for each hand is similar. Furthermore, if the data reveal that for unimanual straight movements, reaction times and movement times are lower than those for unimanual turning movements, as the research in the past would suggest, and if they then reveal that the turning limb in a bimanual act "dictates" the response time for the straight-moving limb (by elongating it from its unimanual condition), further corroboration of the Kelso et al. (1979b) data will have been generated.

On the other hand, indications that the hands only perform in temporal synchrony when movement synchrony exists would reinforce the interference models of Preilowski (1975) and Marteniuk and MacKenzie (1980). That is, this model would predict temporal dysynchrony when the tasks are different for each hand, but synchrony when the movements are mirror images of each other.

Interpretation of bimanual movement times is partially dependent upon the nature of unimanual straight and turning movements. Assuming that differences are apparent in these movements, support for Kelso et al.'s (1979a, 1979b) position would be derived if, (a) movement times for each hand are equal for each hand when performing similar or dissimilar tasks or (b) there is a hands by direction interaction. Any difference between hands in unimanual dissimilar tasks is reduced significantly when the hands are paired together but only if the interaction is such that the "easier" task's movement time is lengthened while the more difficult task's time is relatively unaltered. The Marteniuk and MacKenzie (1980) stance would also be reinforced by a hands by direction interaction

but with the specific requirement that the interaction can be interpreted according to interference and facilitation hypotheses That is, by using, for instance, the bimanual straight movements as baseline values, an increase in the left hand movement time would be predicted by having the right hand perform the more difficult turning movement. Similarly, by taking the bimanual turning movements as a control value the left hand's movement time would be decreased if it was then paired with the right hand moving straight. Such results would be predicted by Preilowski's (1975) efference interference model and have already have been found with both distance and mass as independent variables Marteniuk and MacKenzie,(1980.)

## METHOD

### Subjects

The subjects were 12 college age volunteers (6 male, 6 female) all of whom were right-hand dominant.

### Apparatus

The apparatus (see Figure 1) consisted of a plywood base 56 cm long, 79 cm wide and 5.50 cm thick) mounted on a standard table (73 cm high). Overlying the plywood base was a 1 mm thick sheet of plexiglas which served as the bottom of the track along which the subjects' hands were to move. On top of the plexiglas were placed four 4 mm plywood cutouts which served to described the four possible tracks. At the ends of each track were placed 2 mm thick pieces of galvanized steel serving as start and finish targets. On each of the two pieces which were the starting positions was a triangular piece of nonconducting tape that described exact starting points. The subjects began each trial with both hand-held (pen-grip) metal 4.5 cm long styli resting on the tape apexes. The end-point metal pieces were taped so that 4 $cm^2$ targets (2 cm x 2 cm) were defined. The tracks were designed so that each hand could make two possible movements, each of 37 cm; one, a straight ahead movement and the other a movement which for the first half duplicated the first but which after the halfway point described a smoothed

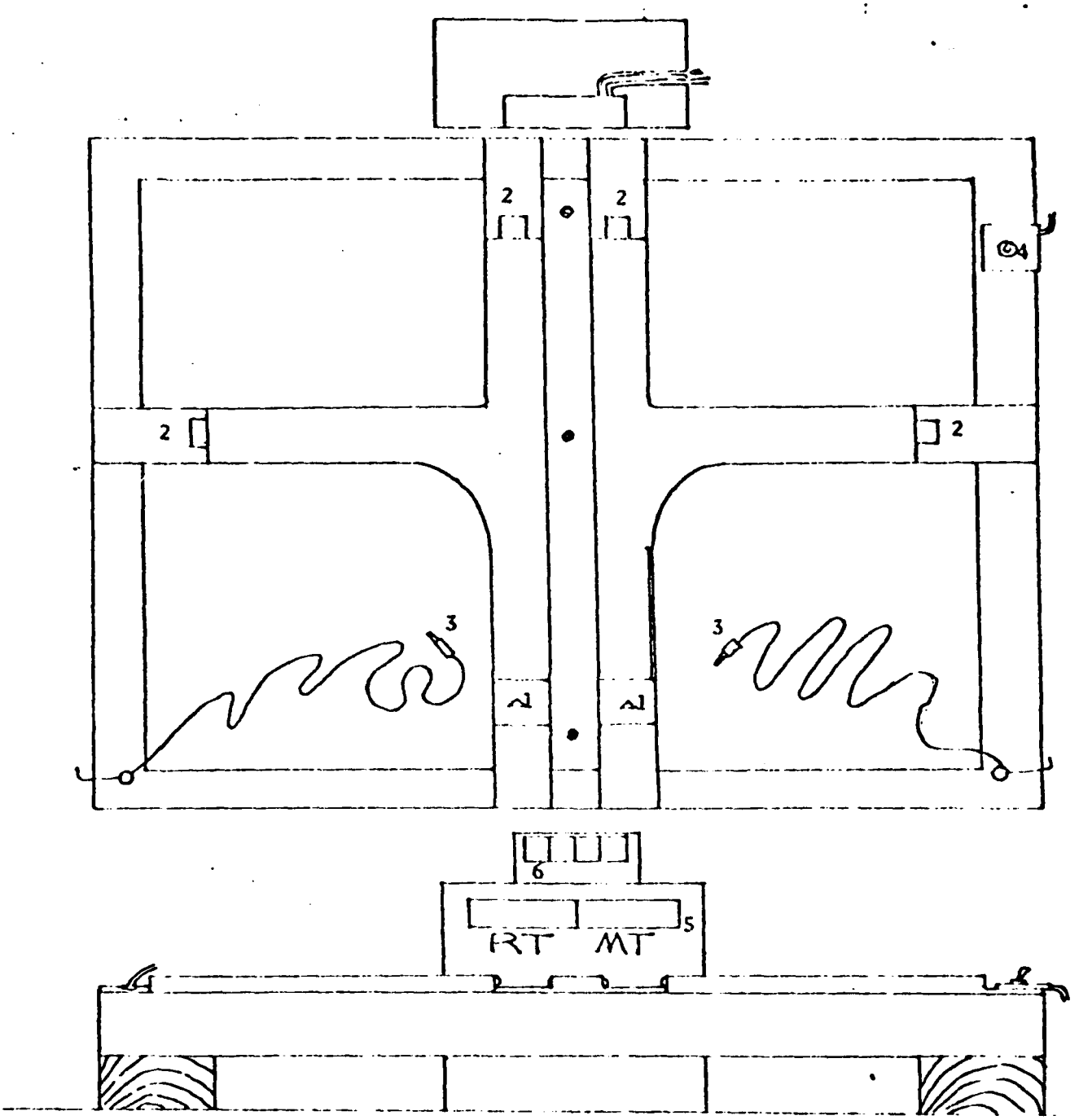



Figure 1: Diagram of experimental apparatus. 1, starting positions; 2, targets; 3, styli; 4, trial switch; 5, reaction and movement time indicators; 6, direction indicators. See text for dimensions.

right-angled curve away from the center-line to the target. The bounds of the track, which were constant 4.5 cm in width, were formed by the plywood sections and specifically by sections of 2 mm thick wire which served to indicate whether any movement was interrupted by a collision with the barriers.

Centered directly 70 cm in front of the subject, who sat at the midline of the apparatus, and at the end of the straight tracks were two metal boxes, one sitting upon the other. The upper box (10 cm by 5 cm by 5 cm) had a 4 cm by 2 cm panel through which four separately lit directional arrows were arranged (each arrow measured 2 cm by 1 cm and was 24 cm above the apparatus. The arrows were arranged to maximize their compatibility with the movements they corresponded to. The lower box (21 cm by 15 cm by 9 cm) displayed RT and MT (the slower of each in the case of two-handed movements) as KR for each hand through its interface with the Digital Equipment Corporation PDP-8e mini-computer and the apparatus. The computer was responsible for initiating all lighted arrow displays with the appropriate (500, 1000, and 1500 msec) interstimulus intervals, collecting and printing out all reaction, movement and total response times, categorizing and listing all task-related errors and performing initial data reduction. The apparatus was wired so that seven different types of errors could be correctly identified; reaction time errors (where the subject either responded to the movement stimulus in less than 100 msec or in longer than 500 msec), movement time errors (where MT was also outside the designated range 100 msec to 500 msec), barrier errors (where the metal stylus touched

the wire track borders), number-of-hand errors (where the incorrect number of limbs responded), target errors (where a correctly moving hand touched an incorrect target), anticipation errors (where the moving hand(s) left the start position prior to the movement stimulus), and errors occurring when the act was initiated but no target was contacted.

While the computer controlled the (random) order of task requirements, a manually operated switch was used by the subject to bring on each subsequent trial. This allowed each subject to determine his or her own pace throughout each testing session.

Task

The task of each subject was to move the hand-held metal stylus from the start position along the track to the designated target as fast and as accurately as possible after receiving the visual movement stimulus, without committing any of the possible errors. The subjects were required to direct visual attention to the light display and not to the hands once the movement task was known.

Procedure

Eight equally frequent (across a testing session) experimental conditions were used. Each trial's characteristics depended on whether the task required a one-handed or a bimanual movement, whether the movement was to be made with the left or right hand, and whether the direction was straight ahead (S) or whether it involved a change in direction (T). The nature of the task was explained to each subject

on each of five days of testing, with the instructions particularly emphasizing speed and accuracy. When each subject indicated comprehension of the task and its requirements the day's trials began.

To begin each trial, the subject flipped the manual switch and the light(s) indicating the task (and warning the subject that movement will be required) were illuminated for a period of one second. The light(s) then went out for the variable foreperiod and the same light(s) were then relit to indicate the movement stimulus. The subject responded as quickly as possible to the stimulus and moved as quickly and accurately as possible to the designated target. On completion of the task, the computer recorded the relevant information, including times and errors, and awaited the subject's flipping of the switch to go on to the next randomly predetermined trial. On each of the six days, each subject received 96 trials, with the qualification that those trials be correctly performed. Any trials on which errors were committed are randomly reinserted in order by the computer, and no data from errored trials were used in the analysis. The order of the entire set of 96 trials was stored in the computer and prior to each testing session a start position was randomly selected so that, theoretically, each subject could receive any one of 96 possible trial orders.

Design and Analyses

A within subject design was employed with the factors Subjects (12), Hands (2), Number of hands (2), Symmetry of direction (3), and Time (2) crossed. Analyses of variance (ANOVA) of both RT and MT were employed, and post hoc analysis by Scheffe's method was performed subsequently. In addition, several nonstatistical tests of phenomena of particular post hoc interest were performed. In all instances a 0.05 level of statistical significance was invoked.

While significant main effects were expected, it was with respect to certain statistical interactions that major interpretative focus was directed. For this reason, it was felt that ANOVA and then post hoc contracts were preferable to a series of contrasts performed in lieu of ANOVA. Error rates were measured and categorized but were not subjected to any statistical tests.

## Results

The experimental results are presented in three divisions; those relating to error rates, reaction time and movement time. Error rates, used here primarily as an indicant in data interpretations particularly of, but not limited to, possible experimental artifacts such as speed-accuracy trade-offs. The RT and MT data are subject to statistical analysis.

### Error Rates

For each of the six designated types of error, Table 1 presents the experiment wide error rate(calculated as being 26.6% on Time 1 and 19.9% on Time 2). It is immediately noticeable that the overall error rate is far higher than might normally seem respectable. By convention, error rates in most research of motor skills seek error rates below 10 or 12%. In consideration of criterion error rates before the experiment was initiated (but after pilot data indicated the likelihood of an inflated rate) it was decided that, given the uniqueness of the task and the desire not to compromise any ecological validity the experiment may have possessed, error rates would reflect actual subject performance. That is, a subject would not forfeit a day's practice if his or her error rate exceeded the conventional criterion. However, the task used, requiring as it did a restrictive trajectory accuracy requirement, might also be considered more difficult than many other experimental motor tasks. In this respect, it is clear that barrier errors account for almost 50% of all errors made.

Table 1: Error Rate Profile for Each Movement Condition, Error Type, Time and Hand (L/R). Note: In Time 1, each cell represents 288 trials; in Time 2 each cell represents 432 trials.

| | | Error Type* | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Time | Anticipation | Barrier | No. Hands | MT | RT | Target | TOTAL |
| S. | 1 | 2 | 5 | 4 | 0 | 4 | 2 | 12 |
| | 2 | 8 | 6 | 6 | 4 | 2 | 8 | 34 |
| .S | 1 | 5 | 6 | 3 | 2 | 4 | 2 | 22 |
| | 2 | 8 | 3 | 7 | 3 | 2 | 3 | 26 |
| T. | 1 | 3 | 43 | 2 | 4 | 8 | 7 | 67 |
| | 2 | 5 | 56 | 5 | 2 | 2 | 8 | 78 |
| .T | 1 | 2 | 18 | 2 | 5 | 4 | 3 | 34 |
| | 2 | 10 | 42 | 6 | 0 | 1 | 4 | 63 |
| SS | 1 | 4/1 | 8/8 | 0/0 | 1/0 | 4/5 | 3/3 | 14/11 |
| | 2 | 3/6 | 3/5 | 0/0 | 2/1 | 7/5 | 4/4 | 19/21 |
| TT | 1 | 15/8 | 40/35 | 0/0 | 19/8 | 4/2 | 20/18 | 88/71 |
| | 2 | 4/7 | 44/37 | 0/0 | 6/4 | 5/5 | 17/15 | 76/68 |
| ST | 1 | 6/6 | 5/37 | 0/0 | 12/23 | 6/5 | 12/26 | 41/97 |
| | 2 | 5/11 | 16/66 | 0/0 | 16/3 | 2/2 | 13/18 | 52/100 |
| TS | 1 | 4/7 | 63/10 | 0/0 | 15/6 | 12/12 | 19/15 | 123/41 |
| | 2 | 8/8 | 103/7 | 0/0 | 15/2 | 7/5 | 22/12 | 155/34 |
| TOTAL | 1 | 63 | 288 | 11 | 95 | 70 | 130 | |
| | 2 | 83 | 388 | 24 | 58 | 45 | 138 | |

*See Method for explanation and definition of abbreviations.

Table 1 also reveals, when equated for cell numbers, that there is a slight decrease in error rate from Time 1 (Days 1 and 2 of practice) to Time 2 (Days 3, 4 and 5) across all error categories. As is discussed in more detail below, this decrease is concomitant with RT and MT decreases, one indication that the data are not contaminated by a speed-accuracy trade-off.

With respect to barrier errors, a number of trends seem to have emerged. Firstly, in contrasting one-handed and two-handed barrier error rates, there is support for the assumption that bimanual acts are more difficult to execute than single hand movements. Secondly, however, it is also apparent that the type of bimanual task influences barrier error rates; there is a remarkable degree of similarity of error levels in symmetrical movements. Although not discernible from Table 1, barrier errors on any one trial in symmetrical movements often (but not always) occurred in <u>both</u> hands. Across all error categories is a reasonably consistent pattern of error rates; higher rates in the movements requiring a change in direction. This trend is particularly conspicuous with respect to barrier, MT, and target errors, and is not restricted to bimanual movements only. Specifically, of the barrier errors committed in the bimanual conditions, 87% were made by the turning hand (87% in the symmetrical movements and 88% in the asymmetrical movements). In the unimanual conditions, 89% were associated with this movement. The barrier errors were committed equally often by the left and right hands in the symmetrical bimanual movements

whereas in the asymmetrical conditions the left hand committed more barrier errors in turning than did the right. However, it is apparent that the trend in barriers was more influenced by the movement direction than by any possible handedness influence. Focus is now directed toward statistical analysis of RT and MT, and possible confirmation of the trend.

Reaction Time Analysis

As mentioned in stating the problem central to the experiment significant main effects for the independent variables were of less-than-crucial importance. However, it was expected that they would all be significant and would be valuable in their provision of a basis of expectation of response characteristics. For instance, a significant main effect of Time ($F(1,11) = 14.33$, $p<0.05$) was expected because performance improvement with practice is one of the most robust phenomena in all of skills research. Beyond this check of the data, the main effects have little value in terms of the theoretical issues being raised. The main effect of direction symmetry revealed a clear increase of RT from the unimanual condition through symmetrical and nonsymmetrical bimanual movements ($F(2,22) = 12.48$, $p<0.05$). Post hoc analysis revealed that the nonsymmetrical bimanual condition had higher RTs than both of the other two, which in turn were not statistically distinguishable.

The basic bimanual-unimanual RT difference was substantiated by the Number of Hands main effect, $F(1,11) = 70.40$, $p<0.05$; two-handed movements being associated with longer reaction latencies than one-handed movements. The mean RT differences between left and right hand (collapsed across all conditions) was not significant, $F(1,11) = 2.61$, $p<0.05$; the left hand taking on average less than 3 msec less time to initiate a response than the right.

It is the interactivity of the three independent variables, direction symmetry, hands, and number of hands, which holds the key to the interpretative conjecture. The ANOVA indicated that three 2-way interactions, all involving these three factors, were significant and that one three-way interaction (again with the factors D, N and H) was significant. It is a characteristic of the ANOVA, however, that is not fully capable of distinguishing what are some very interesting individual hand and direction relationships, for which Scheffe's post hoc procedures were used.

Figure 2 displays RT for each of the unimanual conditions (alone and dual refer to unimanual and bimanual movements respectively). These data are the most inconclusive of the experiment since it is apparent that different things happen during turned movements than during straight movements when performed unimanually. There is no mean RT difference between left and right hands when each moves straight alone (336 msec vs 341 msec), and there is none when they perform

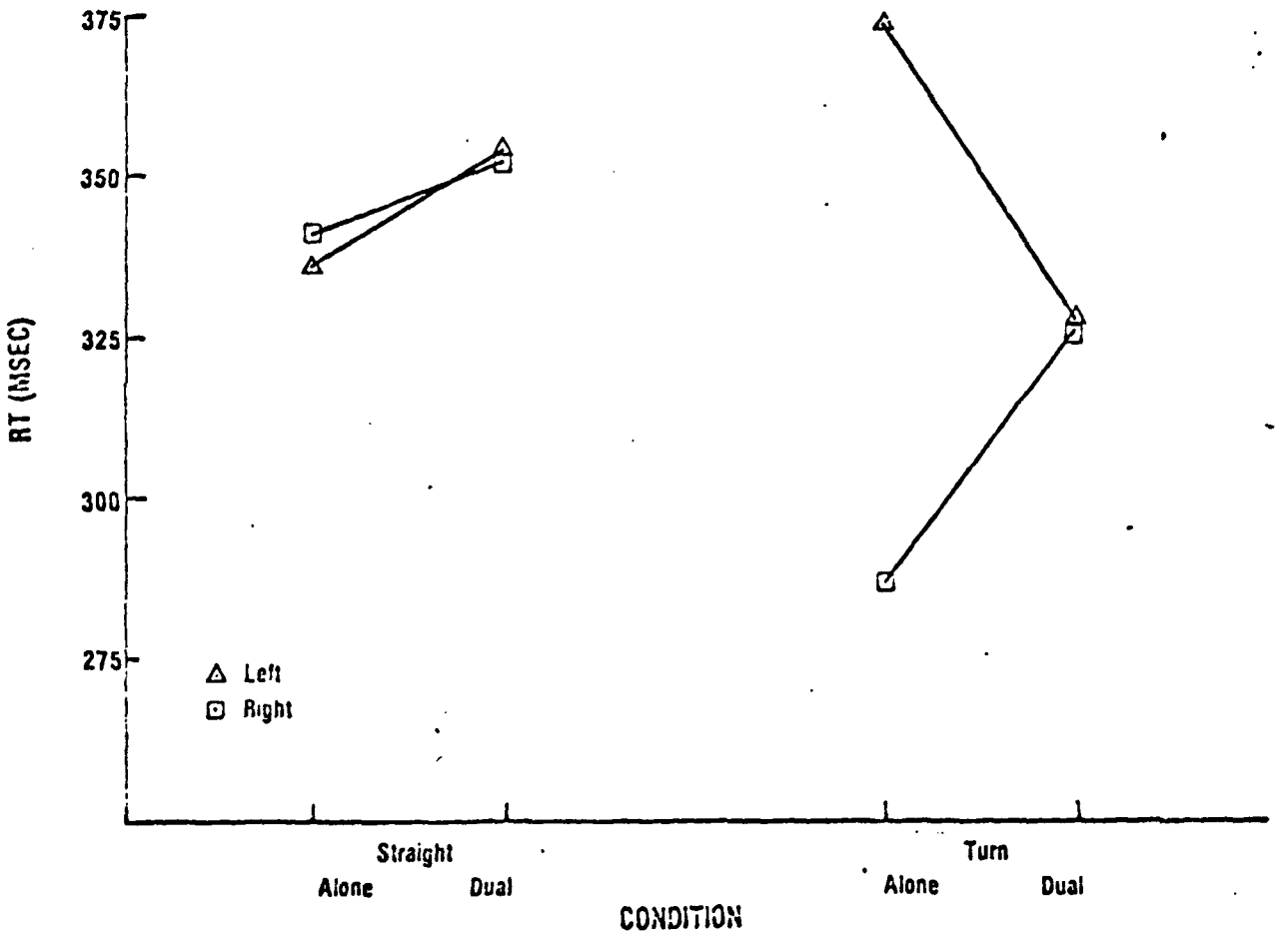



Figure 2: Mean RT(msec) for each hand in unimanual and bimanual symmetrical conditions.

together (although the means are elevated by 18 msec, a significant amount). The turned movement condition, however, follows a very different pattern: the unimanual difference in hands RTs (89 msec) is not only very large but, in relation to the straight-alone condition, is of far greater magnitude. Furthermore, the right hand also has a lower mean RT value than the right hand in the straight condition. This very striking set of data will be discussed below, in conjunction with the MTs of the same condition. Of more interest than either of these observations is the very clear influence of having the two hands perform the same turned movement together rather than individually. The 89 msec difference completely disappears (the mean RT difference between left and right hands in the turn-dual condition is not significant) and it disappears in an unusual way: the left hand, which could react in a mean of 376 msec alone, could react in 329 msec when paired with the right hand! This significant RT decrease is coupled with an increase in RT for the right of very similar magnitude (47 msec and 39 msec, respectively). A large amount of the Discussion is devoted to the explication of these data.

The two conditions, then, had different influences on RT. Two straight movements performed bimanually took longer to initiate than when they were performed individually, but turned movements took somewhere between the RT values of their individual components. That when performed bimanually, RTs for each hand were similar is a consistent finding; the nature of the RTs in relation to the individual conditions makes for more interesting speculation (see below).

Figure 3 displays mean RTs for each of the four bimanual conditions. The SS and TT (transferred, incidentically, from Figure 2) reveal almost identical left-right RTs although they are not, as conditions, similar. The heavy interaction portrayed in Figure 3 reveals that in nonsymmetrical movements, too, left-right RTs are very similar. However, the nature of the RTs seems to be highly dependent on the particular task required of each hand. It is clear, for example, that when the left hand (to go straight) is paired with the right (turning) (ST), its RT is lowered significantly from even the symmetrical condition (SS). The left hand is now reacting more quickly than it did earlier. The right hand turning (the fastest of all unimanual conditions) in the ST condition maintains its RT at the same level as in the TT condition. Precisely the opposite effect appears in the TS condition. The left hand turning alone (T.) is the slowest of the four individual conditions and when paired with the (individually faster) right hand moving straight, slows the right down, to a level significantly higher than in the SS condition.

In both asymmetrical movements, then, it appears that the turning requirement has the major influence on RTs, at least more so than handedness. That the influence can be facilatory and inhibitory is of substantial theoretical significance and will be discussed in more detail below.

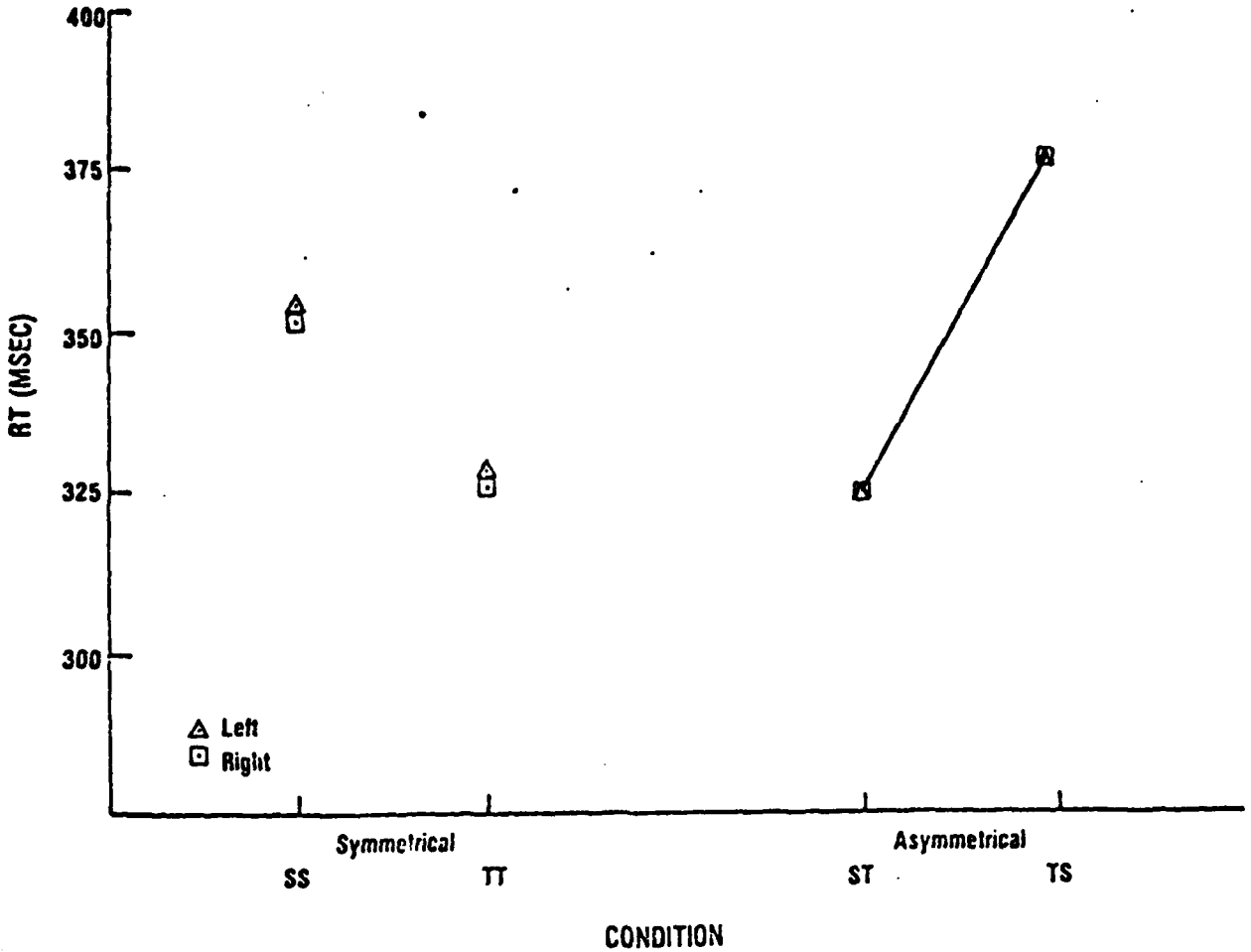



Figure 3: Mean RT(msec) for each hand in symmetrical and asymmetrical bimanial conditions.

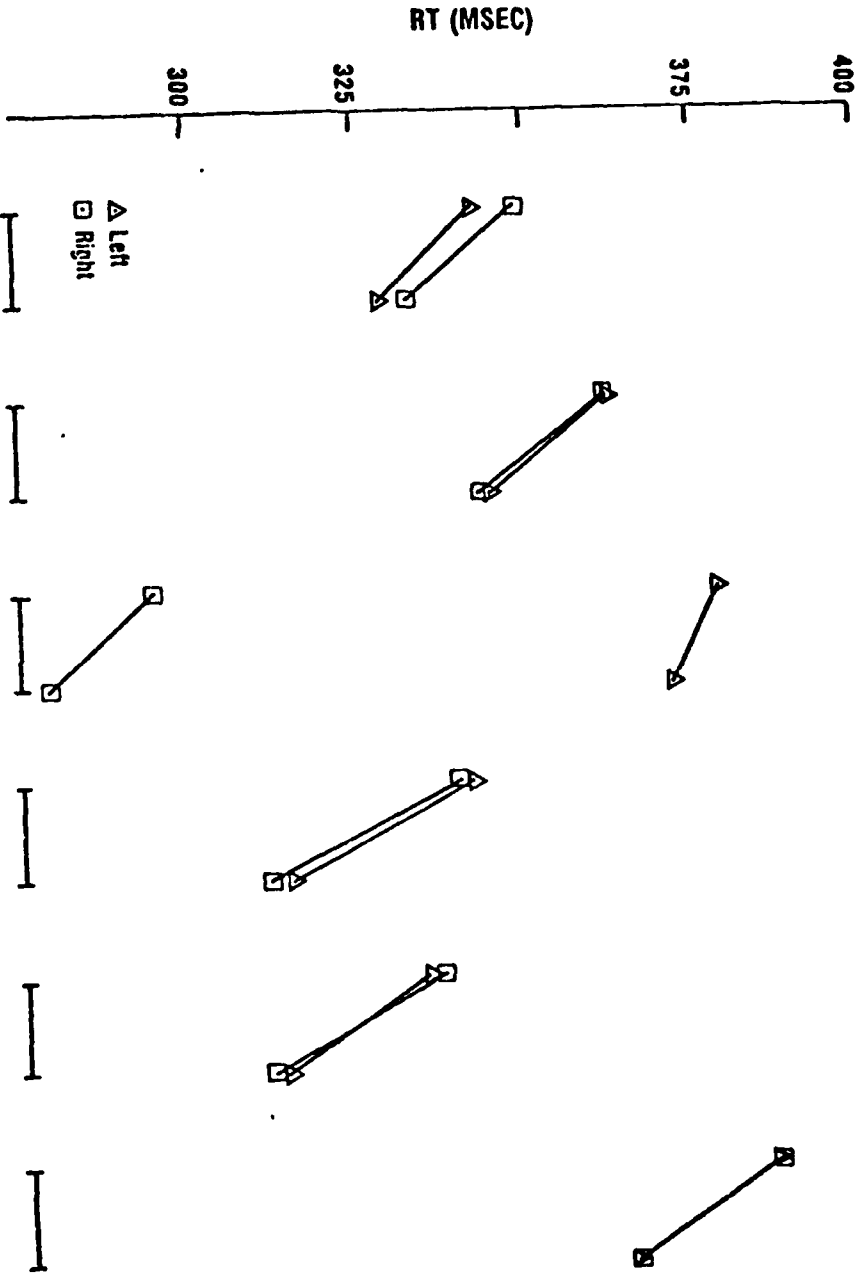



Figure 4: Mean RT(msec) for each hand in each movement condition for each time period.

**Table 2**
**Mean Reaction Times and Movement Times**
**(with standard deviations)**
**and Total Time for each hand and movement condition.**
**Times are in msec.**

| LEFT | | | | RIGHT | | |
|---|---|---|---|---|---|---|
| Total | MT | RT | Condition | RT | MT | Total |
| 618 | 282 (46) | 336 (70) | S. | | | |
| | | | .S | 341 (20) | 256 (41) | 597 |
| 738 | 362 (42) | 376 (70) | T. | | | |
| | | | .T | 287 (22) | 333 (37) | 620 |
| 641 | 287 (52) | 354 (23) | SS | 353 (23) | 288 (53) | 641 |
| 700 | 371 (50) | 329 (31) | TT | 326 (33) | 366 (43) | 692 |
| 659 | 334 (45) | 325 (29) | ST | 325 (33) | 382 (45) | 707 |
| 765 | 389 (43) | 376 (29) | TS | 376 (30) | 336 (44) | 712 |

RT = Reaction time MT = Movement time
S = Straight movement T = Turned movement

Table 2 represents the mean values and standard deviations for RT in the significant DNH interaction ($F$ (2,22) = 217.00, $p<0.05$). Post hoc analysis revealed that in no bimanual condition, symmetrical or non-symmetrical, was there a RT difference between hands. The significant differences were found to be between directions. As noted above, the main effect of time of practice (T) was significant ($F(1,11) = 14.33$, $p<0.05$), yet equally conspicuous is the consistent nonsignificance of T-related interactions. Figure 4 reveals that basic factorial relationships, regardless of their individual significance, were maintained in the second practice period.

Movement Time Analysis

As for RT, *a priori* interest in the main effect of each independent variable was primarily directed toward the checking of expected trends rather than theoretical interpretation. For all four factors, the main effect was significant (for T, $F(1,11) = 17.47$; for D, $F(2,22) = 66.88$; for N, $F(1,11) = 284.39$; and for H, $F(1,11) = 25.63$, $p<0.05$ for each effect). In all cases, the differences were in the expected directions, and for D, post hoc comparisons revealed that unimanual movements, which in turn, were faster than nonsymmetrical movements. Again, it was to the interactions that most of the theoretical and interpretative focus was directed.

The MT ANOVA revealed the existence of only two significant interactions. One, DN ($F(2,22) = 20.95$, $p<0.05$), parallels the RT finding and is indicative of the elevation of response latencies in bimanual task over the unimanual ones. The other interaction to reach significance, DH ($F(2,22) = 14.42$, $p<0.05$), reveals the equalizing influence that bimanual movements

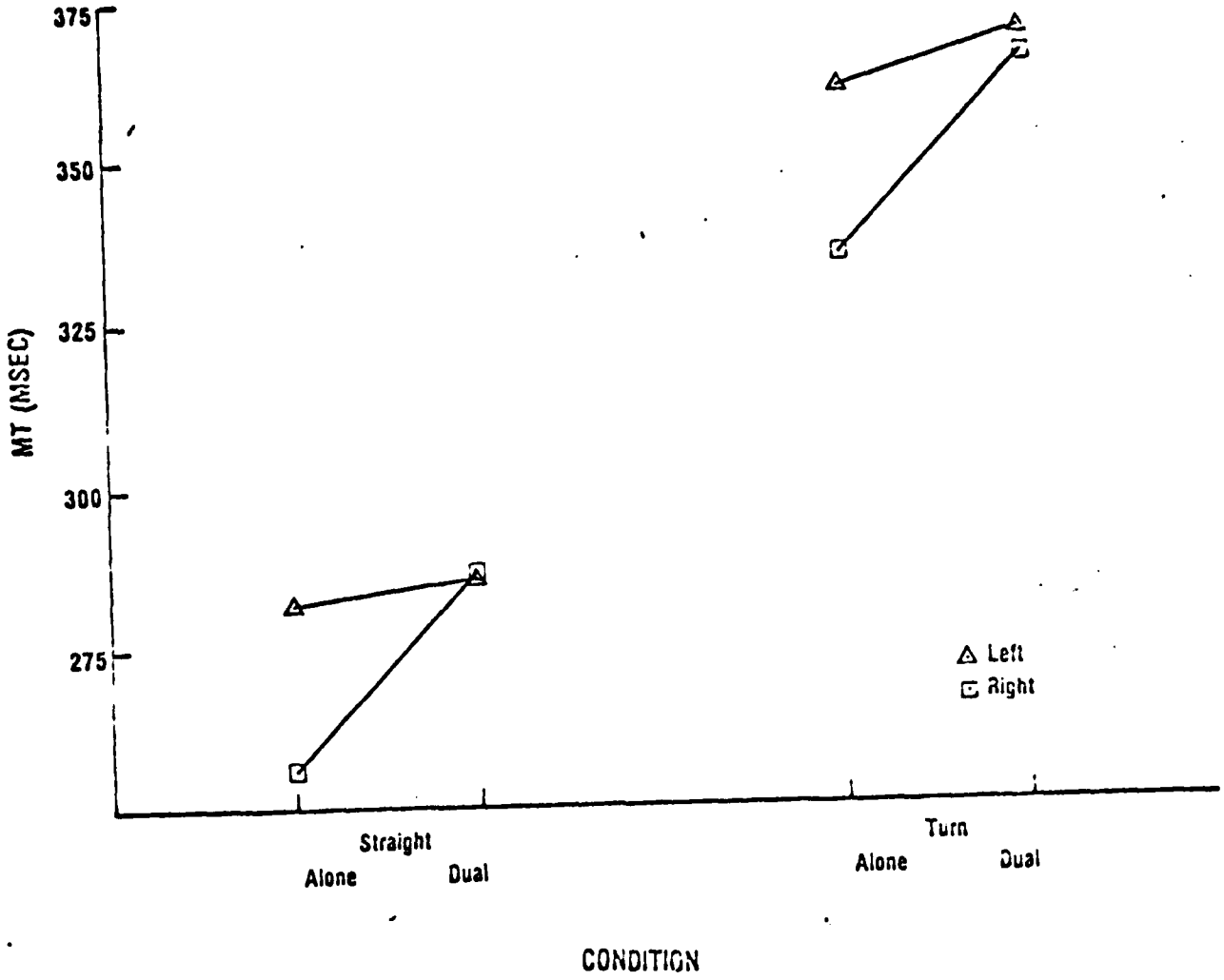



Figure 5: Mean MT(msec) for each hand is unimanual and bimanual symmetrical conditions.

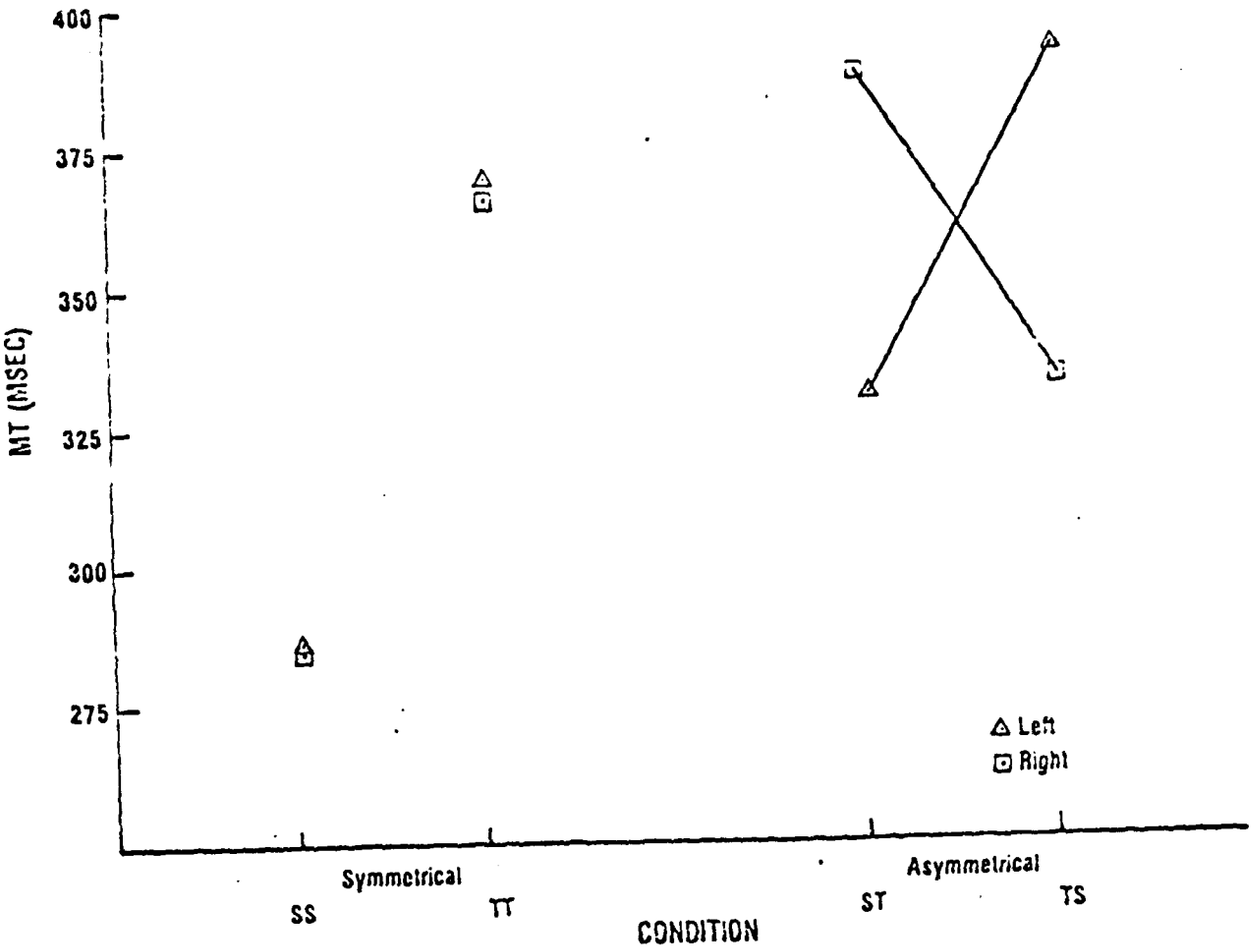



Figure 6: Mean MT(msec) for each hand symmetrical and asymmetrical bimanual conditions.

have over otherwise distinct unimanual hand differences. That is, when the hands make movements individually, the left hand is significantly slower than the right, yet that difference is almost completely irradicated when the same movements are combined in the symmetrical bimanual condition. Figure 5 displays this relationship clearly. In addition, it seems that the left hand, being slower, dictates overall movement latency to the right; in both the SS and TT conditions, the combined MT is no higher than the slower hand was individually.

It is with respect to MT differences in asymmetrical movements that intriguing patterns emerge. Unlike the RT data, which revealed a highly significant DNH interaction, the same interaction for MT was not significant. However, this analysis of the data* effectively clouds what is a distinct and highly interesting result. Unlike the RT data, where the hands began moving at the same time, they did not actually move with the same temporal symmetry. Figure 6 shows that a straight movement (either S(T) or (T)S) had the same mean MT, but since this was a nonsymmetrical movement, it was always faster (by an average of 50 msec) than the hand having to turn en route to the target. This difference was found to be significant by post hoc analysis. The Turn condition had a similar equality across hands (382 msec for the left, 376 msec for the right) and a similar inequality within a task. Comparing Figures 3 and 6 reveals the difference in performance during non-

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*The reason for this lies primarily in the way the data were arranged for analysis; namely, the two straight movements were arranged one against the other, as were the two turned movements. Figures 3 and 6 represent their actual relationship: ST and TS.

symmetrical bimanual movements. Table 2 combines the RT and MT means and standard deviations and reveals clearly the relationship.

As for the RT data, the interactive influence of time of practice was not present. In no case did T enter any significant interaction with another variable as is revealed in Figure 7. Interhand differences (whether significant or not) were not disturbed over the days of practice.

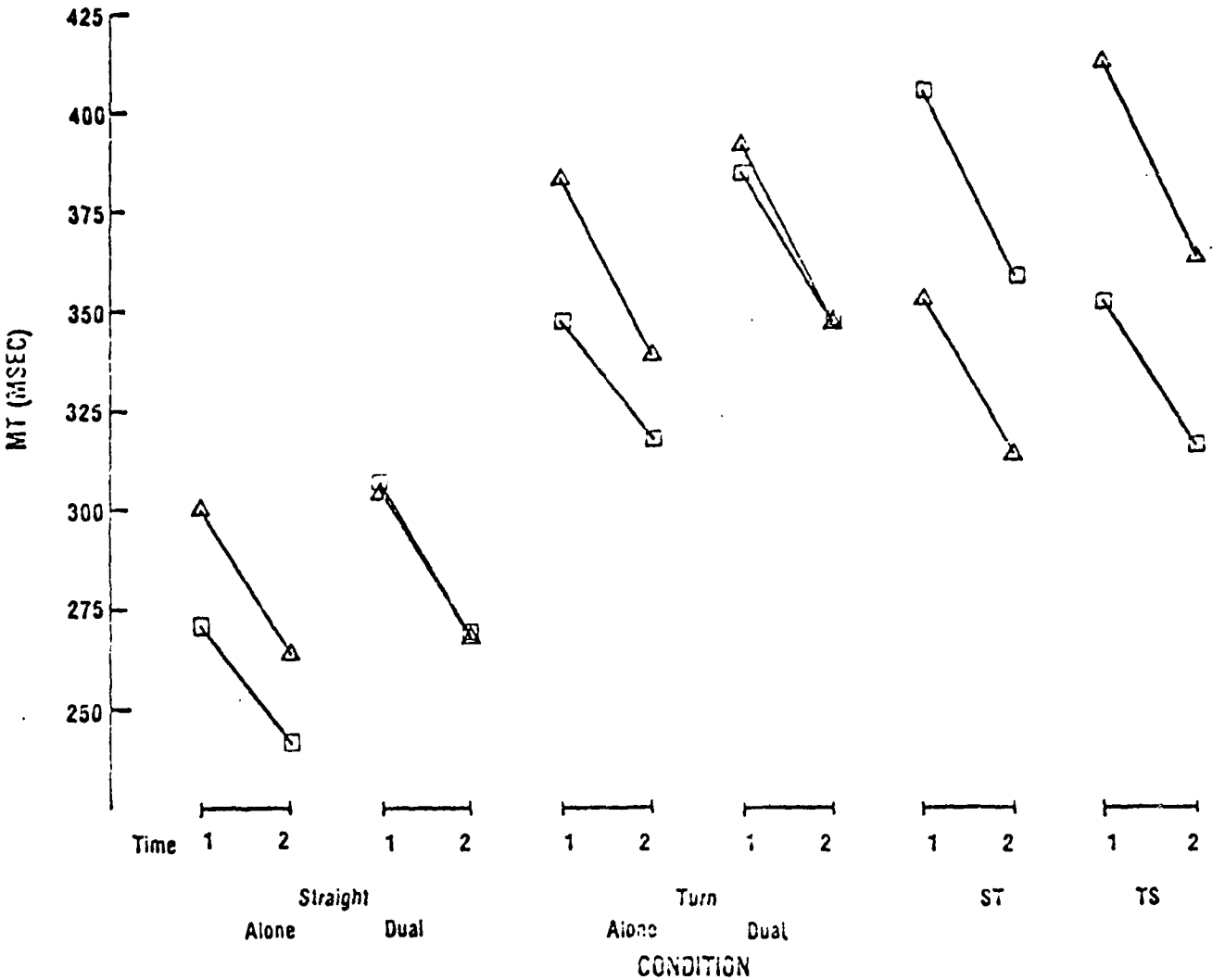



Figure 7: Mean MT (msec) for each hand in each movement condition for each time period.

## Discussion

The primary intent of this experiment was described as an attempt to reconcile recent equivocalities in data and interpretations of bimanual movement characteristics. Given the absence of a substantial amount of previous experimentation, it was not expected that the experiment would completely unequivocate the issues or explain the complexities of two-handed movements. With respect to the intent, the data are essentially inconclusive; at once refuting one position, at another contradicting an alternative account, yet all the while seemingly failing to be consistent in these reversals of refutation. While certain effects, found elsewhere, have been replicated here, the most basic question—whether two-handed movements of differing response complexity are temporally linked--seems to have been only partially resolved. Before discussing the data in terms of broader theoretical issues, however, it is necessary to distinguish the possible methodological idiosyncracies of the experiment from unequivocal experimental effects.

The reaction time data are the source of one of the two major methodological problems. Figure 2 reveals highly disparate RT patterns for the two hands in the two unimanual conditions. That is, when the left and right hands are to make straight movements up the track, there is no difference in their individual mean RTs (341 msec vs. 336 msec). In the turn condition there is a large difference (376 msec vs. 287 msec), and one which is further complicated by the fact that the right hand has a far lower mean RT than the right hand making a

straight movement. It was initially expected that the turn condition, being more complex (Glencross 1973; Henry & Rogers, 1961; Kerr, 1975), would be associated with longer RTs. Instead only the left hand in the turn condition follows this expectation. One possible explanation, for which the error data may eventually be valuable is that in the turn conditions subjects adopt a radical speed-accuracy trade-off strategy, sacrificing movement time for reaction time in the right hand, and the reverse in the left hand. This reasoning would seem to have strong support in the MT results where the right hand in the turn condition is far slower than in the straight condition (see Table 2). It may also be, however, that it is not the data from turn-alone condition (T. and .T in Table 2) which is influenced by a trade-off. Instead, it seems equally, and possibly more, likely that it is the RT for the right hand moving straight which is artificially high. Two points would seem to support this possibility. One, simple RTs, where subjects know completely prior to moving what the task involves, tend to be lower (in other motor tasks) than the 336-341 msec range found here. Values lower than 200 msec are not uncommon is small discrete movements, and even larger movements (cf. Norrie, 1964; Kelso et al., 1979a) report RTs lower than 300 msec. Secondly, if it is only this one datum that is artificial, and if it is imagined to be at a truer, lower level (e.g., 250 msec) the unimanual RTs seem to be aligned as expected.

Nonetheless, there are three reasons--none individually convincing perhaps--which cast some doubt on the only-a-trade-off explanation. Firstly, the trade-off issue can also (and not necessarily independently)

be described in terms of MT and error rates, and in this respect it does not appear totally convincing that subjects are sacrificing MT at all; error rates are consistently higher in both unimanual turn conditions than in the two straight movements despite the mean MTs also being higher. Furthermore, a trade-off explanation would, prima facie, seem to require application to more than just one potentially spurious datum point; the others, here, do not seem accommodating in this regard. If subjects are using a trade-off strategy it does not seem to have been very successful. A second reason for mediating against the trade-off reasoning is that subjects were explicitly instructed to avoid utilizing such a strategy (after pilot data indicated a similar pattern). Thirdly, the pattern of results was noticably consistent across all 12 subjects. It seems difficult to accept the argument that every subject would ignore explicit instructions about adapting such an approach, especially when the instructions were repeated at least daily and often during the testing session.

There may, however, also be one silver lining in this methodological cloud. The fact that a large and highly significant unimanual interhand RT difference exists makes it almost complete irradication in the bimanual condition even more pronounced. (It remains unfortunate that there was no unimanual difference between hands in the straight condition--one there, and its subsequent removal when performed bimanually would have greatly enhanced the interpretative power of the data). Such a finding, to this extent of analysis, is consistent with the data of Kelso et al. (1979a) and Marteniuk et al. (Note 1). It is the direction of the DH interaction wich offers more pertinent clues as to the organization of bimanual movements. Neither of the aforementioned papers reported interactions of the type found in the turn condition. Like

the straight condition, they both found elevations of bimanual RTs over unimanual RTs for the same movements.

In the nonsymmetrical bimanual movements (ST and TS) neither the Kelso et al. (1979a) nor Marteniuk et al. (Note 1) position is supported particularly well. While RTs are identical for each hand (despite their having to move differently) it is the turn which determines the overall RT level. In the case of the expected data being actually gathered this would strongly support the Kelso et al. position, but as was mentioned, the expected data were not the gathered data, and it seems as if a RT can be altered to an equal and opposite degree when paired with a left or right turn. The reaction time data, then, alone do not provide any clear support for either theoretical position. Are the movement time data any more supportive? Analysis of the main effects and interactions would seem to suggest that, yes, there are consistent trends, ones which would give weight to the Preilowski (1975) - Marteniuk and MacKenzie (1980) model of bimanual interference.

According to this account, when movements of differing difficulty (and the 'difficulty' need only be a term arbitrarily given to empirically generated unimanual condition differences) are performed bimanually, 'neural cross-talk' interferes with the performance of the limbs, altering the temporal pattern of both, but not to the extent of making the MTs equal in each hand.

Figure 5 displayed the two significant interactions generated when unimanual movements are combined in symmetrical bimanual task. The data are highly consistent with those reported by Kelso et al. (1979a) and Marteniuk et al. (Note 1); any MT differences existing in the unimanual condition are absent in the bimanual condition, and the

level of the bimanual MT is similar to that of the slower unimanual MT (i.e., the slower hand dictates movement speed to the faster hand).

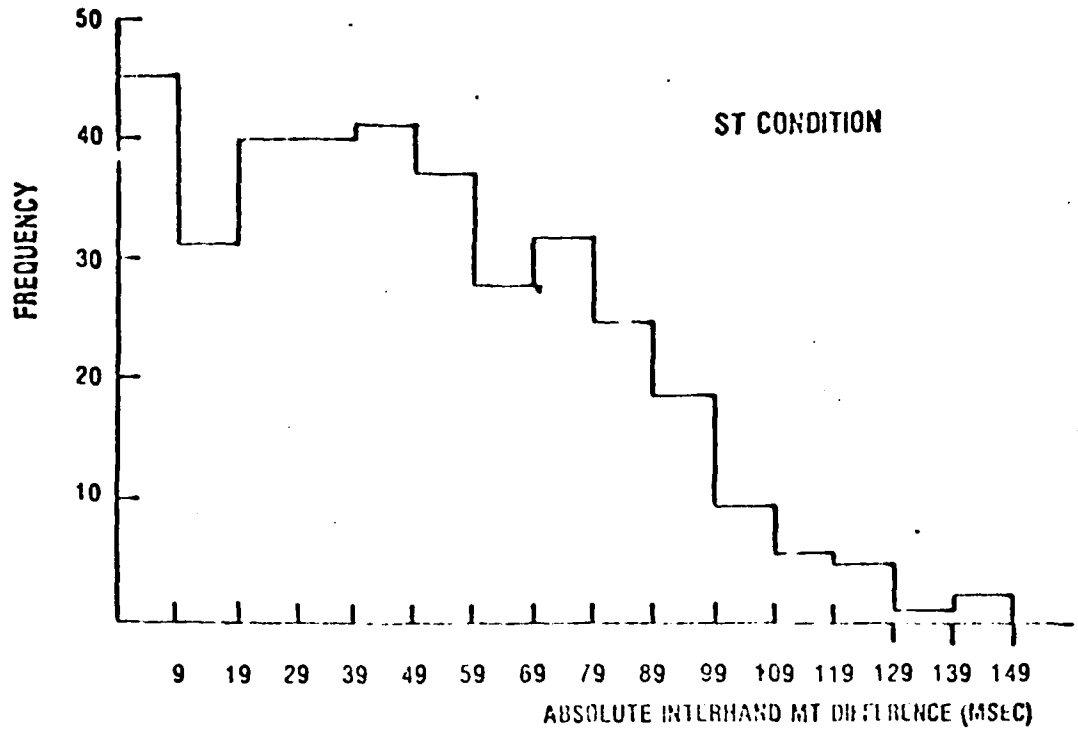
It is with respect to nonsymmetrical bimanual movements that the data seem capable of distinguishing between models and predictions. Figure 6 clearly showed that MT differences which exist between unimanual directions are maintained when combined bimanually, the turn condition has significantly slower MTs than the straight condition in the unimanual, symmetrical bimanual, and nonsymmetrical bimanual conditions. Kelso et al. (1979a) reported that 80% of the total response time difference under unimanual conditions disappears in the nonsymmetrical bimanual condition. Analysis of Table 3 reveals that in this experiment the difference reduction* (from 143 msec to 102 msec) was only on the magnitude of 28.2%, an amount more consistent with the Preilowski-Marteniuk model. The data are indicative of temporal differences across hands in bimanual tasks of differing complexity, and run counter to Kelso et al.'s (1979a) claim that, like more innate interlimb acts such as locomotion, temporal linkages between limbs spontaneously and consistently arise. Although their data are supportive of an extension of the model derived from such evidence to discrete movements of varying amplitudes, it does not seem to have found support here where direction changes were required.

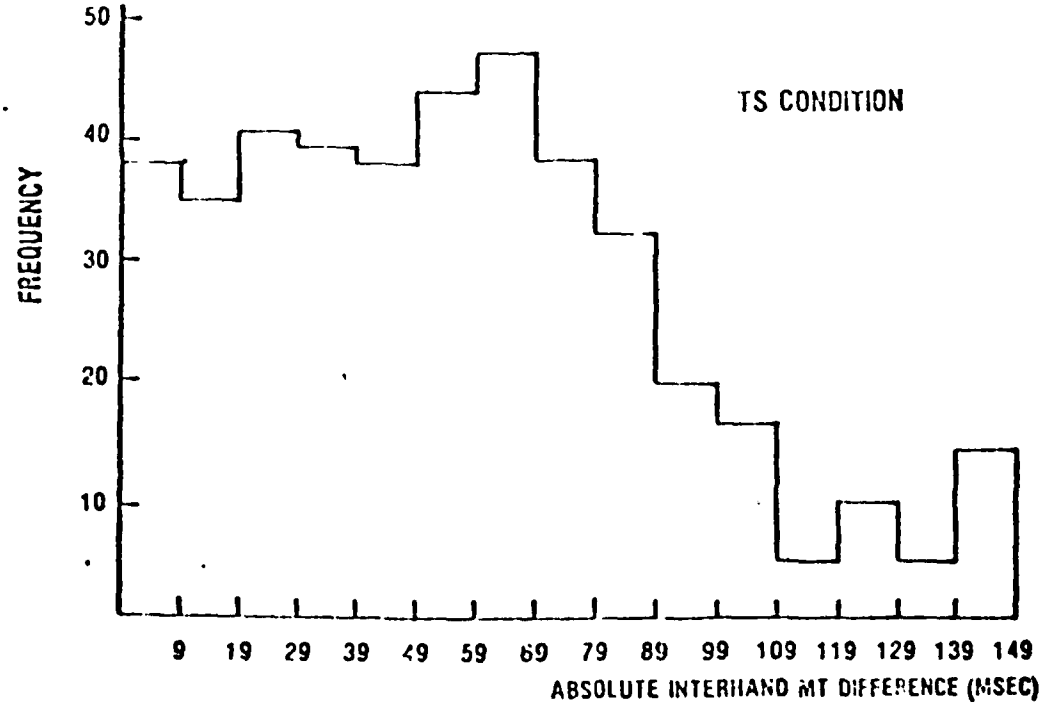
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*The total time mean of (T. + .T) from (S. + .S) contrasted with the S means in ST and TS and the T means in ST and TS.

However, there is one important issue that may serve to accentuate the nongenerality of bimanual organization. Unlike both the Kelso et al. (1979a) and Marteniuk et al. (Note 1) experiments, which used button pushing tasks, this experiment required subjects to slide along a defined track to a target. Although the target did not traverse the entire track (and therefore made terminal accuracy a priority 'specification' in preparing or executing the response), it did not force the subjects to make a strict movement termination. Instead, merely contacting the target was sufficient to stop the MT clock(s), and although the experimental instructions included a directive to stop on the target, and not pass through it, there was no control that such was actually taking place. It was felt that the construction of barriers preventing target overshoot would not fully control the problem since subjects could then rely on the barriers to terminate the movements. This would not require any more definite 'specification' than no barriers.

In attempting to resolve the question of whether the MT differences were robust or were, as Kelso et al. (1979a) might argue in defense of their model, merely a function of the task requirements, the absolute MT differences between hands were plotted as a frequency distribution. Within interpretative limits, it seemed likely that if the data were indeed robust and consistent phenomena the frequency distribution would reveal a unimodal point close to each mean value (48 msec for the ST condition, 53 msec for the TS condition) with a reasonably leptokurtic characteristic. On the other hand, if the (imagined) rebuttal was fair, the frequency might be observed to be more scattered across each of the intervals (more platykurtic perhaps). Figures 8 a and 8b


ST CONDITION
FREQUENCY
50
40
30
20
10
9 19 29 39 49 59 69 79 89 99 109 119 129 139 149
ABSOLUTE INTERHAND MT DIFFERENCE (MSEC)


TS CONDITION
FREQUENCY
50
40
30
20
10
9 19 29 39 49 59 69 79 89 99 109 119 129 139 149
ABSOLUTE INTERHAND MT DIFFERENCE (MSEC)

show that there is some justification to the argument that the differences are not consistent, and therefore not robust or useful in the way of theoretical interpretation. Both reveal negatively skewed distributions (without being particularly leptokurtic).

There is other evidence, however, that the bimanual organization model proposed by Kelso et al. (1979a) is not unassailable. One premise that it has is that bimanual actions are organized as one functional muscle collective. Even if the above concerns relating to this premise are temporarily overlooked, their model also seriously implies the consistency of such an organization. However, it should be recognized that evidence for such premises has been primarily extracted from mean RT and MT data; that is, from data which, when presented, may have washed out crucial individual trial characteristics. For instance, in this experiment the mean condition RT values may imply that there is a powerful interlimb coordination. Such is not necessarily the case. In an attempt to determine the correlational characteristics of limb differences in RT and MT, individual trial data were subjected to a linear regression analysis for each of the four bimanual conditions. It was expected that if temporal invariance between limbs is a robust phenomenon, and not one artificially created by the use of mean values, the correlated hand differences for RT and MT would be high and negative in all four conditions. Linear regression analysis revealed that even for symmetrical bimanual movements the correlations are not high ($R = -.51$ for SS; $R = -.49$ for TT), and for the nonsymmetrical conditions, they are of zero-order magnitude ($R = -.07$ for ST; $R = -.17$ for TS).

Even without the emphasis on the correlation coefficients, and although the mean difference for RTs is near zero, there is a wide range of values, in both the positive and negative directions. Clearly, the consistency reflected in mean values produce a somewhat distorted picture of actual trial-by-trial fluctuations in temporal coordination, and the argument that interlimb coordination may be instantaneously generated--as Kelso et al. (1979a) maintain--seems strained. It should be noted, however, that they also reported very high within-subject correlations between hands in all bimanual movements (although the dependent variable(s) used in the analysis were not mentioned). It is felt that the correlations used here were equally, if not more, representative of interlimb timing characteristics than single RT, MT or total time analyses since they involved both RT and MT inter-hand differences.

Conclusion.

Three key issues provided the impetus for the experiment: one, the perceived need for more evidence which could accentuate the impotence of models of motor behavior developed through mechanistic devices and computer metaphors while at the same time furthering the cause for ecological valid research; two, the development in recent years of a concerted scientific interest in two-handed movements; and three, the ambiguities existent in current explanations of bimanual task organization.

This experiment has, we are convinced, important things to offer philosophical-methodological arguments in motor behavior. For example, the data, whatever their more detailed ambiguities, do reveal that what can generally be established as scientific fact in one-handed movements, can only--and should only--be restricted to such movements; they do not transfer well to bimanual movements. Regardless of the theoretical model one might advocate, it is apparent, not only from these data but also from those of Kelso et al. (1979a) and Marteniuk et al. (Note 1), that there is genuine interactivity of the two limbs: they do not operate independently. If nothing else, the experiment may increase the caution with which researchers seek to transfer, apply and recombine their data. This experiment, to the extent that the data are methodologically irreproachable, adds weight to the argument (outlined above) that there is far more to the operation of the human action system(s) then unimanual data can reveal.

It is with respect to the finer aspects of the data, however, that ambiguities arise such that further work becomes especially critical to better understandings. The possibility of minor methodological artifacts notwithstanding, the data seem to offer particularly compelling support for Marteniuk et al.'s (Note 1) model of two-handed coordination.

This model (originally developed by Preilowski, 1975) predicts that when two hands are required to make nonsymmetrical movements there is a neural interaction during output of two (for want of a simpler term) motor programs such that the normally slower hand can be made to move more quickly through its unintended 'pilfering' of the command to the faster limb. This interaction, Preilowski suggested, could occur at any and/or every level of the neuraxis prior to exit to the individual limbs.

However, there is another animidaversion to which this interpretation can be subjected. Although the data reveal clearly that the MTs of individual hands do not undergo any temporal linkage when the tasks are asymmetrical, it is not equally clear that the type of task used here is sufficiently 'like' the others used to warrant a wholesale transfer of interpretation. Earlier, it was noted that unless very stringent terminal accuracy requirements are made there is the possibility that MT is not particularly appropriate dependent variable.

Reference Note

1. Marteniuk, R.G., C.L. MacKenzie & D.M. Baba, Simultaneous control of upper limb movements: information processing and neural interaction effects. Unpublished manuscript, 1981.

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# *Rapid Error Corrections:*

# Evidence for Internal Feedback

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Virginia A. Diggles

## INTRODUCTION

There has been much discussion concerning the importance of information generated within the central nervous system. Indeed a debate over the essentiality of central versus peripheral information has dominated the motor control literature for many years. Experiments aimed at clarifying the functional significance of what may be termed the central commands from the brain and sensory feedback from peripheral receptors resulted in a debate over which is the dominant source of information for movement regulation (Laszlo, 1966; McCloskey, 1973; Taub & Berman, 1968). The major issues were kept at a restricted level: the centralists repeatedly demonstrated the ability of organisms to perform certain types of motor acts in the absence of feedback and the peripheralists repeatedly demonstrated performance decrements when feedback was degraded (Glencross, 1977; Schmidt, 1977; Stelmach, 1979). It became clear that neither a strict central nor a strict peripheral explanation in isolation could explain adequately all phenomena observed. More recent attempts have moved toward examination of the interaction and integration of these two sources of information and away from their dichotomy (Bizzi, 1980; Cooke, 1980; Capaday & Cooke, 1981; Turvey, Shaw & Mace, 1978).

One aspect of this central-peripheral debate that has received much attention is the notion of internal feedback (Anokhin, 1969;

Evarts, 1971; Ito, 1974) which refers to the duplication of efferent activity that remains in the central nervous system for a variety of possible purposes. The functions this information may serve, the form it may take, and its destination are topics which have seen intense research and speculation.

Much of the early investigation on efference copy and corollary discharge involved the study of eye movement and perceptual stability, however application to other perceptual and motor systems has also been examined (McCloskey, in press; Miles & Evarts, 1979). Of specific interest here is the role of internal feedback in the phenomenon of rapid error corrections. This phenomenon has been observed most often in step tracking tasks and choice reaction tasks where errors in direction are observed to be corrected in less time than response latencies to external stimuli. The explanation offered in most cases posits that errors were detected centrally via the efference copy, even before the movement was begun. Therefore the corrections were not in response to the external consequences of the error but to its earlier specification in the original efferent command.

The idea that efferent copies are monitored for errors has been a convenient explanation of this phenomenon and has received considerable empirical examination. However, many of the studies conducted to substantiate central monitoring of efference have found only partial support due to methodological and theoretical issues. Differences in what constitutes an error, how and where

to measure errors, and which analysis is appropriate here obscured meaningful comparisons and a comprehensive approach to the study of central monitoring of efference. Further examination of the concept is warranted to rectify some of these issues. And, in light of a recent alternative advanced by Schmidt and Gordon (1977) to explain rapid error corrections, experimental differentiation of the two plausible hypotheses is indicated. The present study sought to examine the phenomenon or rapid error corrections in the context of choice reactions where variables of expectancy, efferent activity, and efferent complexity are manipulated.

The possible benefits to be derived from the study of rapid error corrections revolv mostly around the acquisition of information. As a phenomenon, it has implications for sporting situations and man-machine interfaces where response time is critical. In these situations, individuals often respond to external information, and the importance of internal information is not emphasized. More importantly, study of these phenomena may make substantial contribution toward identifying forms and functional usages of internal communication within the central nervous system. Such information could also be useful diagnostically in the evaluation of some motor disorders. Since rapid error corrections occur naturally and are beneficial, their study usually concentrates on determining the mechanisms responsible.

# REVIEW OF LITERATURE

This review of literature is organized in two sections. The first section introduces the concept of internal feedback in the nervous system and evidence suggesting that such pathways exist and may subserve the function of feedback loop. Ways in which the efferent command may benefit movement other than perceptually are examined in the second section on central monitoring of efference, concentrating on the phenomenon of rapid error corrections and the false anticipation hypothesis.

## Internal Feedback

Feedback, in an engineering sense, is that property of a closed loop system which permits the output (or some other controllable variable of the system) to be compared with the input to the system (or an input to some other internally situated component or subsystem) so that the appropriate control action may be formed as some function of the output and input. Often in motor behavior literature, feedback is restricted to information arising only as a direct consequence of muscular contraction and movement, a limited application of the term. There is abundant anatomical and physiological evidence to show that the output of the neuron is directed not only to some target in a sequential chain of neural and motor events but is also fed back onto the neuronal

systems that initiated it (Evarts, 1971). As such, it is no less important than the feedback of the response. Internal feedback provides a vehicle by which the signals that are generated centrally in the nervous system to control a movement may also be compared with a reference mechanism centrally, yielding an appraisal of correctness without contribution of peripheral feedback. Pathways leading from motor to sensory, motor to motor, and sensory to motor areas demonstrate this recursive nature of the central nervous system. Indeed, there appears to be a variety of pathways information from the motor cortex may take to return to sensory systems: via the pons and cerebellum, via the dorsal column nuclei, and via the interneuronal pools of the spinal cord (Evarts, 1971).

Cerebro-cerebellar connections have received large amounts of investigative attention as loci of internal feedback, predicated in part by their massive interconnection and the fact that the cerebellum receives input from peripheral sensory areas also. Ito (1974) suggested that these interconnections allow the cerebellum to monitor cortical output and feedback corrective signals to cortex in order to correct errors of cortical output long before this output gives rise to motoneuronal discharge. The dynamic loop hypothesis of Eccles et al. (1967) maintained that in response to a pattern of pyramidal tract discharge (motor command) the cerebellar nuclei can compute the correctness of the command and return a modified version to the cerebrum, resulting in corrections prior to useful peripheral input. The estimated time for information to

traverse this loop is around 20 msec.

Having established that possible pathways exist, what other evidence is there to support the notion of internal feedback? Internal feedback demands that there be predictable discharges in the centers mediating this feedback preceding movement. Thach (1970a,b) found some cerebellar nuclei cells that fire well before movement and suggested that cerebellar activity could modify cortical output after its issuance but prior to any movement. Evarts (1973) also found cells in the precentral cortex, basal ganglia and cerebellum that all discharge prior to movement. He demonstrated that the ventralis lateralis of the thalamus and the cerebellum, both pathways from the motor cortex back to itself, discharge prior to learned movements (10-110 msec prior) and well in advance of response feedback (Evarts, 1970). Evarts (1974) also recorded some single units in the postcentral, sensory cortex that modified their discharge prior to the onset of muscular activity, suggesting a type of motor output from the sensory cortex. However, Bioulac and Lamarre (1979) demonstrated that the neurons of the primary sensory cortex cease to be influenced by movement when the animal is deafferented, suggesting that the discharges observed to be modified by movement both before and after the movement are mainly the result of sensory feedback from the periphery.

Further indication of loops that may monitor central events is found in certain afferent paths that reflect the activity of lower motor centers and are only indirectly concerned with peripheral

events. Oscarsson (1970) reported a fairly long internal feedback loop through the ascending pathways to cerebellum which may be involved in signalling events within the CNS. The ventral tract neurons of mesencephalic cats with deafferented hind-limbs continued to discharge during locomotion just as they had prior to sectioning, suggesting that these neurons were dependent upon descending commands at the segmental level, not peripheral input. While these ascending pathways appear unsuitable for specific peripheral information, they are suitable for carrying information about the activity in pools of interneurons that are simultaneously reflex centers and links in descending pathways. Oscarsson (1970) speculated that this internal feedback loop assesses the planned movement by relaying its effect on lower motor centers back to the cerebellum for further modification.

## Central Monitoring of Efference

In addition to the proposed perceptual role of internal feedback, two informational roles have also been hypothesized. The first role assumes that movement information coded in the efferent command is available to the individual. Accessing this information allows him or her to localize objects in space and to learn and perform movements in the absence of sensory feedback. The second role involves the detection and correction of errors in the efferent command. In either case, the nervous system is seen to monitor the efferent command centrally, extract the required information, and alter behavior accordingly. Jones (1977) suggested that a copy of the information sent to the muscles is

also sent to a storage location in the central nervous system where this efferent copy is monitored centrally, eliminating the delays inherent in the delivery of peripheral information. Thus movements can be carried out in the absence of peripheral information and/or corrected without external error information. This latter role of central monitoring of efference will be considered in the next sections.

## Rapid Error Corrections

The phenomenon of rapid error corrections has been observed in saccadic eye movement, step tracking tasks and choice reaction tasks (CRT) where errors in direction are corrected with latencies shorter than response latencies to external stimuli. Central monitoring of efference has been proposed as the source of these rapid corrections; hypothetically, errors in the efferent command are detected centrally even before the movement has begun. Therefore, corrections are not made in response to external consequences of the error, but instead to its earlier specification in the efferent command. Thus, what is usually seen following the stimulus to move is the start of an incorrect movement followed soon after by a reversal to the correct direction.

The first section reviews some of the interpretations of corrective saccadic eye movements in the dark. The second group of studies on rapid error correction utilized the task of step tracking where subjects were required to track a signal which periodically deviated from its home position by steps (as opposed to ramps or sine waves). The third section on error corrections include some early work on serial choice reaction tasks (Rabbitt, 1966, 1967, 1968) and more recent studies on discrete choice reaction tasks.

Corrective Eye Movements. Rapid error corrections occur in eye movements as well as in limb movements. They are observed when the eyes move from one target to another using two saccades, the first saccade under- or overshoots the target and the second, corrective movement brings the eyes on target approximately 125 msec after the first saccade (Becker & Fuchs, 1969; Weber & Daroff, 1972). Retinal information cannot be the sole indicator of this visual error since the corrective saccades occur in darkness also. What then is the stimulus for this second saccade when no retinal information is available?

Becker and Fuchs (1969) investigated the effect of changes in target position ($\pm 5^{o}$) on parameters of the corrective eye movement. If the change occurred coincident with onset of the initial saccade, the corrective movement would arrive successfully at the new location but its latency was extended to that of a normal reaction time (240 msec). If the change occurred 70 msec after termination of the initial saccade, two types of responses occurred: either the second saccade occurred after a fast latency (160 msec) but was directed to the previous (now incorrect) target, followed by a third corrective movement to the new target after a normal reaction time; or the second corrective movement went to the new target position but only after an unusually long latency (366 to 413 msec). The authors suggested that large fixation changes may be preprogrammed as a package composed of two movements: a large movement which always falls short or long of target, and a smaller, corrective movement to the target. Since direction and amplitude are already built into the "package," the visual error sampling time can be significantly reduced, explaining the decreased latency of the second saccade and its occurrence in the dark. The findings indicated that when target changes occurred early enough, the original packaged response could be abandoned and a new program adopted. If the target change was not detected early, the package was carried out to its termination before another response could be generated.

Weber and Daroff (1972) rejected Becker and Fuchs' (1969)

"prepackaging" explanation due to the great variability within and between subjects with regard to possible errors (undershoots, overshoots, binocular and uniocular errors, etc.). They contended that this variability was uncharacteristic of preprogrammed movement and demonstrated two distinct types of involuntary, corrective eye movements. The fast, saccadic corrective movement occurred in binocular errors with a short, well-defined latency (124.5 ± 10.5 msec). When subjects were asked to voluntarily refixate a target latencies ranged from 369 to 468 msec, supporting Becker and Fuchs' (1969) claim that these corrections occur independent of visual feedback. The second type of corrective movement was of low velocity and occurred in only one eye following uniocular errors. This corrective movement was termed glissadic, being accomplished through a gliding movement who's initiation was continuous with the termination of the initial saccade, producing no latency. The authors' preferred explanation utilizes internal monitoring of actual oculomotor output at the brainstem level to explain the corrective eye movements; if the acutal output is discrepant from the intended output, a corrective movement is generated by the pontine paramedian reticular formation. Weber and Daroff (1972) minimize the usefulness of feedback from the stretch receptors of the extraocular muscles, citing the inability of this source of information to explain the glissadic corrections.

Later, Shebilske (1975) claimed support for the functional use of extraocular muscular feedback or feedback from some internal

monitor in the control and perception of eye position. He demonstrated that corrective eye movements were truly corrective; that is, the magnitude and direction of the corrective saccades were highly correlated with the similar error parameters, even when no retinal information could be used. Shebilske (1975) employed psychophysical techniques to determine whether subjects used actual (inflow) or intended (outflow) eye position to localize a second target. The second target appeared 70 msec after the end of the initial saccade but prior to any corrective movement. It was located either in the same location as the original target or on the subject's fovea (fixation point of initial saccade). Subjects were asked whether the second target appeared in the same position as the first. They responded correctly with respect to actual target position, indicating the use of an extraretinal signal that encodes actual rather than intended eye position.

Two points should be made regarding Shebilske's (1975) arguments. First, Shebilske (1975) did not distinguish whether the reliable extraretinal signal was due to feedback from extraocular muscles or an internal monitor; he considers both to be mechanisms of the peripheralist-inflow model. However, the internal monitor model referenced (Weber & Daroff, 1972) clearly refers to prenuclear feedback prior to any motoneuron discharge, and would not be considered an inflow mechanism by many (Evarts, 1971; McCloskey, in press; Schmidt, 1977). Second, Shebilske (1975) attributes a rather rigid assumption to outflow theory. Shebilske

states that "outflow faithfully represents eye position" (p. 625), but interprets this assumption to mean outflow necessarily represents intended eye position. Literally interpreted, this assumption indicates either no errors are possible or all errors are intended; neither concept is defensible in a context where errors occur. Although Shebilske (1975) demonstrates support for the relevance of inflow information, he seems unfair in his representation of outflow theory considering this restrictive assumption and designation of one mechanism to inflow models thought to correct errors in outflow models.

The evidence for internal control of corrective eye movements is divided; although a preponderence of the findings have been interpreted as supportive (Barnes & Gresty, 1973; Becker & Fuchs, 1969; Weber & Daroff, 1972), there is some evidence indicating that extraocular muscular feedback is also a salient source of eye position information (Shebilske, 1975; Skavenski, 1971, 1972; Skavenski & Steinman, 1970).

Step Tracking. All of the step tracking studies reviewed here utilized nearly identical test displays. Oscilloscopes with reversible polarity displayed two vertical lines (or dots) in either the vertical or horizontal axis. One line was the target to be tracked; the other was the response cursor, controlled remotely by the subject via a joystick. The time to correct an error was measured by the interval between the onset of movement and the onset of deceleration for a reversal.

Given this experimental paradigm, Angel and Higgins (1969) systematically reversed the polarity of the scope, thereby inducing an incompatible stimulus-response relationship. Reversal significantly increased the number of errors and error reaction times. However, amendment latencies of errors were significantly faster than correct movement durations, although in this experiment they bordered on a simple reaction time. Later, Higgins and Angel (1970) compared error correction times to simple proprioceptive reaction times (latencies to respond to movement of the lever). In every subject proprioceptive reaction times were much greater than error correction times, suggesting that rapid error corrections could not be based on proprioceptive information.

Attempting to eliminate vision as the possible source of rapid error corrections, Angel, Garland and Fischler (1971) placed an opaque screen across the center of the scope. The subject was unable to see the response cursor until he or she had moved it at least 1.9 cm off center. A block of 4 steps with normal polarity was followed by a block of 8 steps with reversed polarity. Here, similarly to the Higgins and Angel (1970) study, only errors occurring in the reversed polarity trials were analyzed, excluding the first trial after reversal. A total of 24 false moves were initiated, 16 of which were arrested while the cursor was invisible. Angel et al. (1971) concluded that following the initial error on a reversal, subjects had information that would determine the "right" motor program for the following seven target steps. In subsequent

responses, this "right" program is compared to the actual program and any discrepancy would be corrected on the basis of this central information.

There are a number of apparent problems with the Angel et al. (1971) work. First, because no measure of reaction or correction times were reported, one cannot be sure that the corrections that did occur were rapid. Second, errors in normal polarity were not reported making it difficult to determine the cause of errors. If, as previous research indicates (Gibbs, 1965; Higgins & Angel, 1969), incompatible stimulus-response relationships make errors more likely (possibly through more complicated processing in the translation of the information for preparation of the response), then this comparison should be made. It is also possible that errors following the initial error due to reversed polarity may, in part, be due to lapses in memory regarding the current polarity. The conclusion that attributes these corrections to central monitoring of efference based on these data does not seem justified.

Angel (1976) more recently failed to rectify these potential problems when he compared correct and error responses in a visual simple reaction time task, a choice reation time task, and a choice reaction time task where vision of the response was prevented. As in earlier studies (Angel & Higgins, 1969; Higgins & Angel, 1970), the polarity determining the stimulus-response relationship was altered, in this case, after every 10 trials for the choice conditions. In comparing simple and choice responses, the time to correct an

error once it was begun was less than a choice reaction time but statistically no different than a simple reaction time. This finding appears to deny the existence of rapid error corrections since they could be explained as visual reaction times. A third experiment attempted to eliminate this explanation in a way similar to the Angel et al. (1971) study. Unfortunately, he followed the same procedure and arrived at similar conclusions. He expanded the protocol to calculate the efficiency (success) of the hypothesized efferent monitor and compared it with the efficiency of the mechanism responsible for the initial movement. The monitor turned out to be more accurate by approximately 9%.

Although Angel (1976) and his co-workers have studied rapid error corrections extensively, the artifacts of their methods have detracted from the support they sought to provide. Jaeger, Agarwal and Gottlieb (1979) have taken a slightly different approach to the study of rapid error corrections, although their visual display was similar to these previous studies. Assuming three general types of feedback (knowledge of results, primarily visual; proprioceptive, as from spindles; and central, as in corollary discharge). They set out to manipulate each of these sources. Subjects responded with plantar or dorsiflexion of the ankle to the step input while reaction times and correction times were measured by electromyography (EMG). Polarity was reversed after every 8-12 trials to disrupt the first source of feedback: the relationship between vision and proprioception. To disrupt the other sources of

feedback, the subjects wore vibrators over the distal tendons of the soleus and anterior tibalis to interfere with proprioception. To interfere with central processes, a second condition required subject to perform the task at blood alcohol levels of .06-.07%. The third condition was a control group. Correct reaction times in both simple and choice tasks were slower for the altered conditions than for the controls. Error reaction times reflected the same pattern of latencies as correct reaction times whereas error correction times were unaffected by these manipulations. A conclusion that these corrections represent a central source of feedback is supported by the invariance of the error correction times.

An earlier, but perhaps more comprehensive study of step tracking and errors was conducted by Gibbs (1965). Using a step tracking task with five choices instead of two, Gibbs used the unique positional properties of his targets to convey probability. The five targets were aligned horizontally and each position as well as each possible pair of successive positions was used with equal frequency. For example, there was a 3 to 1 probability that a target as position #2 would move to the right rather than to the left to position #1, the reverse being true for position #4. Thus in these conditions the respective outermost targets are "improbable" while the others were "probable." Responses beginning at position #3 were "equi-probable" while movements from positions #1 or #5 were unequivocal with respect to direction. Response latencies, the interval between stimulus onset and movement, and

amendment times, the interval from the beginning of an incorrect response to the commencement of an amended move, were recorded for groups with normal or reversed scope polarity. As before, incomplete data for the normal polarity group restricts this interpretation. Normal polarity resulted in both far fewer errors, and in mean reaction times for all responses that were 40 msec faster than the reversed group. Within the reversed polarity group, both the number of errors and the reaction times to correct responses decreased as probability increased. However, there appeared to be a slight trend for error reaction times to increase as probability increases, amendment times remaining relatively stable. With the improbable target, error reaction times were faster than correct reaction times, demonstrating the typical speed-accuracy tradeoff. Surprisingly, these reaction times were equal when probabilities were equal. In the probable and unequivocal conditions error reaction times were greater than correct reaction times demonstrating the benefit of expectancy on the subject's response strategy. Gibbs' data demonstrated the invariance of amendment times to probability manipulations and a significant learning effect over 100 trials.

A summary of the findings in step tracking tasks includes the following observations: stimulus-response incompatibility results in a larger incidence of errors (Angel & Higgins, 1969; Higgins & Angel, 1969; Gibbs, 1965); for the most part when probabilities are equal, error reaction times are faster than correct reaction times

(Angel, 1976; Angel & Higgins, 1969; Jaeger et al., 1979); error correction times are shorter than both simple and choice reaction times (Angel, 1976; Higgins & Angel, 1969; Jaeger et al., 1979); vision does not play a major role in error corrections (Angel et al., 1971; Angel, 1976; Gibbs, 1965); and error correction times appear to be quite resistent to manipulation in all these studies.

Choice Reaction Tasks. A very similar task to step tracking is the choice reaction task. In this section two types of choice tasks are reviewed: serial and discrete. In a serial choice reaction task, several stimuli are presented continuously in series and reaction times and movement times are included in response latencies. Errors in this context are performed by hitting the wrong key. Discrete choice tasks present one stimulus to which the subject must make a directional response. Errors arise when movement is initiated in the incorrect direction and are corrected when initial movement decelerates and reverses.

Rabbitt (1966a,b, 1969) and Rabbitt and Phillips (1967) performed a series of experiments using the serial choice responding task to systematically examine errors and their corrections. The theoretical framework supporting these experiments posits errors to be non-random events that require the transmission of additional information relative to correct responses. In an error response, not only must the subject select the correct response but they must also detect the incorrect response in progress. A possible reason

error reaction times are faster than correct reaction times is that subjects have partial advance information regarding the response he should have made and so responds more quickly. Rabbitt (1966a) began by studying errors and the context in which they appeared in the series. He found the usual pattern of latencies in which error and error correcting latencies were shorter than correct responses. Rabbitt also found correct responses which immediately followed errors to be longer than other correct responses. Whether there were four or ten choices had no effect on this pattern. Rabbitt (1966b) also demonstrated the independence of rapid error corrections from external visual feedback by testing subjects on a display which gave no indications of error.

Rabbitt (1968) later attempted to separate the two processes he believed were involved in error corrections. To examine the selection process in correcting an error, Rabbitt required subjects to respond to their own errors in three different ways. In the first condition subjects responded with the correct response they should have made. The second and third conditions required subjects to respond to errors with a "common detection response" consisting of: condition 2 in which subjects pressed a key not used in the task to all errors, and conditions 3 in which they responded to all errors with a key used in the task. It turned out that subjects correct their own errors faster and more accurately when they use the appropriate response than an unrelated response. Error detection when the correct response need not be specified was no

longer than when selection must occur. Thus, the selection process does not appear to contribute much toward the corrective response. Indeed, the results here suggest that the nature of the intended response is intimately tied to the corrective procedure, and not simply the consequences of a selection process. Rabbitt also concluded that information regarding the response was total, not partial.

To probe the contribution of error detection to the correction process, Rabbitt and Phillips (1967) altered the stimulus-response compatibility of their task by requiring mirror image responses to the same stimuli. To eliminate any contribution of response selection, a two choice serial reaction task was used so that to correct an error the subject had only one choice - the opposite of the response in progress. The direct mapping condition resulted in fewer errors and faster reaction times. For both mappings error correcting responses were faster than either correct alternations or repetitions. Although error correcting responses were slower in the mirror image condition this difference disappeared with a small amount of practice (See Larish, 1980 for trials effect on incompatibility). Thus, error correction also appears to be insensitive to stimulus response compatibility, at least in this study, the first to make an overt comparison.

Megaw (1972) employed several techniques to examine directional errors in a discrete choice task. The apparatus consisted of three lights in a horizontal array with a response pointer mounted

two types of error in the system. The first type occurs at the execution stage when the chosen response is incorrect, and requires feedback for error correction purposes. The second type of error occurs within a stage of processing, particularly the stimulus identification stage. At this point, if there is insufficient sampling or incomplete classification of the stimulus, response selection will be premature, possibly incorrect. A model capable of explaining this type of error requires that such errors are corrected at the stage of processing where they were committed. The results obtained by Megaw (1972) resemble errors of the latter type, incomplete processing, explaining the faster reaction times on errors. Megaw postulated the need for a central monitor of efference that would account for error correction reaction times shorter than normal latencies. Megaw also suggested the possibility that subjects may be guessing by preselecting a response which is influenced by subjective expectancy (anticipation).

Schmidt and Gordon (1977) proposed two alternative hypotheses to central monitoring of efference to explain rapid error correction results. Each is based on the assumption that subjects anticipate on error trials. Evidence for incorrect anticipations is along two lines: first, the studies that have reported rapid error corrections have had constant foreperiods, creating the opportunity to anticipate; second, the reaction times for correct responses are usually longer than for incorrect responses, suggesting that subjects are incorrectly anticipating on error trials. The two alternative

hypotheses advanced by Schmidt and Gordon (1977) differ in the parameter being anticipated. The first experiment tested the hypothesis that subjects anticipate both the direction and the time of stimulus arrival, while the second experiment tested the hypothesis that only spatial anticipation is responsible for rapid error corrections. Both hypotheses suggest that errors occur and are corrected in the following way: a) the subject generates the expected sensory consequences of the stimulus situation prior to stimulus presentation, this includes the expected consequences of both the stimulus and the response produced feedback (Schmidt, 1976); b) the stimulus is presented and compared to the expected stimulus and an error is signaled; c) this error serves as a stimulus for initiation of the correct response; d) since an incorrect response has been already activated, some of the incorrect response is visible until the correct one begins.

The reaction time for the error is short, due to anticipation. The latency for the correct move is one reaction time plus a psychological refractory period after the stimulus. The result is the initiation of an incorrect response followed closely by the correct response. Schmidt and Gordon (1977) preferred to consider the period from stimulus presentation to the initiation of the correct response as the critical interval of time representing correction time. Correction time is the sum of the error reaction time plus the error correction time.

To test the first hypothesis, that subjects anticipate both temporally and spatially, Schmidt and Gordon (1977) required subjects

on a pivot in front of the subject. The center light was a foreperiod warning light while the others were targets to which the pointer was directed. Measures of displacement and acceleration were recorded from the pointer on paper. Each trial consisted of a warning light followed by one of the other lights with a duration of 80 msec. Each of the stimulus lights occurred with equal probability in a random order. Analysis was limited to directional errors, characterized by responses in the wrong direction initially followed by a reversal to the correct target. The reaction times to these error responses were significantly shorter than for correct responses. Error correction reaction time was designated as the interval between initiation of the incorrect response and the first sign of amendment to the correct response. This value was estimated both by displacement and acceleration recordings. The two estimates differed from each other by 30 msec, although each was faster than a normal reaction time (92 msec for displacement and 63.5 msec for acceleration). Under the experimental procedures performed, the subject knew the correct target to move to when the stimulus was presented. However errors could not be detected through visual feedback, since the stimulus was extinguished before error reaction time was complete.

Based on the finding that error correction reaction time was shorter than normal reaction time and that error reaction times were shorter than correct reaction times, Megaw (1972) provided the following explanations to account for the results. He distinguished

to perform a two choice reaction time task with the direction of the responses randomly ordered. Half the subjects performed the task with a constant foreperiod while the other half performed under variable foreperiods. The frequency of errors in the two conditions did not support the first hypothesis. According to this hypothesis, preventing temporal anticipation (variable foreperiod) should result in fewer errors with rapid corrections, since the subject relies on temporal predictability to anticipate. This was not the case, with each condition having nearly the same number of errors. In addition over 50% of the errors in the variable condition possessed error correction times less than 120 msec.

The second hypothesis posited by Schmidt and Gordon (1977) maintained that the subject anticipates spatially but nor temporally. In doing so, the subject reduces a two choice task to a one choice task, thus reducing the reaction time. The error detection-correction process is the same as in the first hypothesis. Experiment II tested this hypothesis by varying the predictability of the order of the stimulus directions, left or right. In one condition the order of presentation was random; in the other the order was highly predictable, e.g. L, L, R, L, L, R, etc. In the latter condition, deviations from the order were included to induce errors. Anticipation in the predictable sequence condition was evidenced in significantly shorter reaction times in all responses. Similar to previous findings, reaction times in correct responses were longer than for error responses.

Schmidt and Gordon (1977) reasoned that if errors are the product of anticipations, the correction times for both random and anticipation conditions should be equal. Although the correction times differed by 40 msec (random = 331 msec, anticipation = 291 msec) this difference was not significant. When the components of the correction times were examined, error reaction times decreased in the anticipation condition (64 msec, a significant drop from 208 msec to 144 msec) while the error correction time remained relatively unchanged (a non-significant increase of 28 mesc from 116 msec to 144 msec). Schmidt and Gordon concluded that, with the exception of error reaction times, the time course of errors and their corrections were roughly similar for the two conditions, suggesting that errors in both cases are mediated by the same process. This rationale though appears to "beg the question": If one variable is altered (anticipation) and "similar" results are obtained, logic would seem to dictate that this variable was not responsible for the findings. Reaction times for errors decrease as anticipation increases, a covariance that is found in correct responses as well. That reaction times decrease on unexpected trials is odd, since the speed-accuracy tradeoff reverses when probabilities are unequal (Gibbs, 1965). What has been shown is that error correction times are insensitive to different levels of anticipation.

Research on rapid error corrections in choice reaction tasks have led to the following observations: the number of choices does not alter the pattern of reaction times for correct and error

responses (Rabbitt, 1966a); the trials following an error had longer reaction times, as if the subject were adopting a more cautious strategy, if only for two trials (Rabbitt, 1966a); visual feedback is not necessary for rapid error corrections (Rabbitt, 1966b); an important observation is that the time to amend an error is resistant to the type of corrective responses (Rabbitt, 1968), the stimulus response compatibility (Rabbitt & Phillips, 1967), and the level of anticipation (Schmidt & Gordon, 1977). This finding would perhaps be expected in the case of a "hard-wired" internal feedback loop.

Although many aspects of rapid error corrections have been examined empirically, the most striking finding is the failure of any empirical manipulation to alter the error correction time. Indeed, the only evidence of disruption of error correction times has been in populations with pathological disorders such as parkinsonism (Angel, Alston & Higgins, 1970; Flowers, 1975) in which the primary symptom is impairment of voluntary movement. The present investigation manipulated additional variables (anticipation, efferent activity, and efferent complexity) to determine their effect on choice responses and errors. The aim of this study was to add to the existing information regarding rapid error corrections and the possible mechanisms through which they are achieved.

## EXPERIMENT 1

In previous research, afferent information (visual) of the error was precluded to determine if it was the source of rapid error corrections (Angel et al., 1971; Angel, 1976; Megaw, 1972; Rabbitt, 1966b). Error correction times were found not to vary and it was concluded that rapid error correction was a central phenomenon. A more stringent test of the central monitoring of efference would involve removing efferent information while preserving the afferent information associated with the response. In this case efference would not be available for monitoring purposes

and error correction times would be no faster than normal choice reaction times. If removal of efference did not affect error correction times, an argument against central monitoring of efference would result.

Additionally, a second test of the anticipation hypotheses advanced by Schmidt and Gordon was included. The crossing of efference-no efference conditions with anticipation-no anticipation conditions provided the experimental setting to empirically distinguish which variable was responsible for rapid error corrections. Experiment 1 compared choice reactions and error responses when efference is present (active) and when it is absent (passive) crossed with two levels of anticipation, low (random stimulus order, 50% probability) and high (patterned stimulus order, 90% probability). In the active conditions subjects performed a normal two choice reaction task, generating their own correct and error responses. In the passive condition, the apparatus performed the task, generating both correct and error responses. The subject only responded on error trials, reducing the choice response task to one of passive error detection. Conditions for appropriate control comparisons were also collected.

The purpose of Experiment 1 was to determine the importance of efference to rapid error corrections by comparing reaction

times (RTs) and error correction times (ECTs) under active and passive movement in a choice reaction task. The active condition did not differ from traditional choice response paradigms where subjects respond as quickly as possible to one of two stimuli following a warning light and random foreperiod. The passive condition attempted to emulate the afferent information of the active mode but removed purposeful efferent activity. That is, the warning light and stimulus light were delivered as in the active case and after a constant interval (analogous to a RT) the arm was moved passively in the direction of the stimulus light. The subject's task was to monitor the visual and proprioceptive afferent information; no response was required unless there was a mismatch between stimulus direction and movement direction, e.g. left stimulus light and right arm movement. The subjects essentially detect an error present in the afferent input but not internally generated. The central monitoring of efference explanation would predict that subjects cannot detect externally generated (passive) errors as rapidly as internally generated (active) errors. Although removal of efference (passive movement) is known to differ from active movements in ways other than simply its absence (spindle sensitivity for example), these deviations are predictable and were taken into account when comparing these types of movement in the discussion.

The false anticipation hypothesis (Schmidt & Gordon, 1977) suggested that anticipation is responsible for rapid error corrections. To test this hypothesis, low and high anticipation conditions were crossed with active and passive movement modes. Anticipation used here as an experimental variable, referes to stimulus predictability. The anticipation hypothesis predicted that the patterns of error latencies would be similar between anticipation conditions. The combination of the two variables (anticipation and efferent activity) factorially permits observation of their interaction. This manipulation represents a partial replication of the Schmidt and Gordon (1977) study and attempts to distinguish between anticipation and central monitoring of efference as the possible source of rapid error corrections.

Method

Subjects. Twelve, right-handed, male subjects were recruited from the University of Wisconsin to participate in each condition of the within-subjects design.

Apparatus. The apparatus consisted of two units, a control console and response unit (see Figure 1). The response unit presented subjects with a visual display, a response lever (5 cm in length), and a digital readout of the times variables. The visual display consisted of a centered warning light, flanked

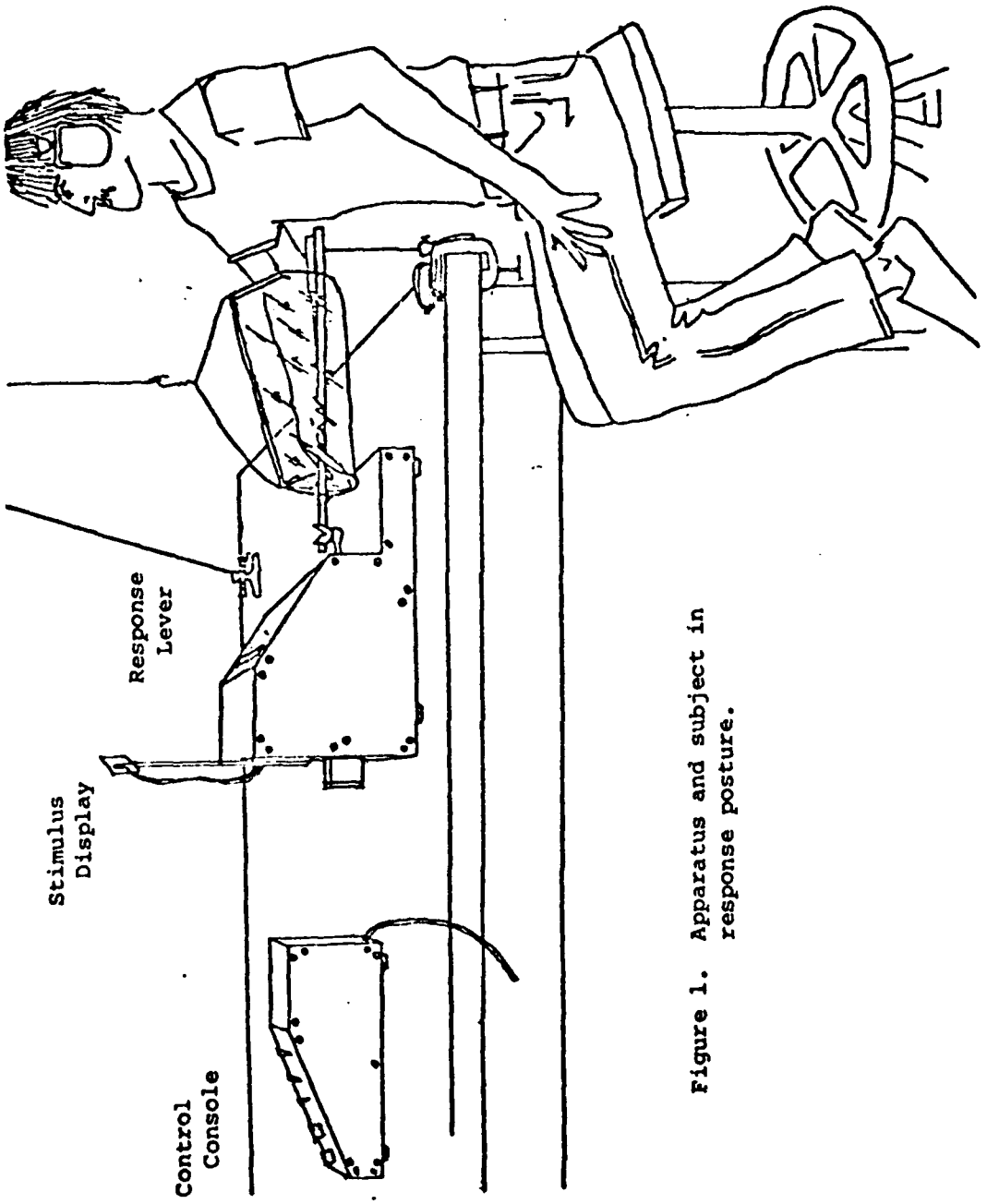



Figure 1. Apparatus and subject in response posture.

by left and right stimulus lights (duration = 100 msec), all within foveal vision (approximately $4^{o}$ visual angle). This display was mounted 22 cm above the unit to keep the responding limb and apparatus out of foveal vision. Possible warning light durations were .5, 1.0, and 2.0 sec.

The response lever extended horizontally from the control box and could be moved 5 cm from the center "home" position in either direction. This position was marked by a ball-detent, requiring 10941.36 Newtons of force to free the lever. In the passive mode a 451.9 Newton-mm torque stepping motor engaged the lever carriage to move it through the full range of motion in either of the directions. To disengage the lever from the motor required the same resistance to overpower and the ball-detent. The delay between stimulus and motor onset was set at 450 msec, based on pilot data.

Microswitches on either side of the lever carriage activated two decade counters in the control unit after a 1 mm movement. One decade counter was activated by initial movement in the wrong direction and was deactivated by movement reversal to the correct direction. This quantity represents error correction time (ECT). A second decade counter started when the stimulus light came on and stopped when the lever was moved in the direction signaled by the stimulus. This quantity represents total time to achieve a correct response, thus on correct trials it represents an RT and on error trials it represents RT + an error correction time (ECT).

To support and immobilize the wrist and arm, an elbow-to-fingers air splint was placed on the subject's arm. A plastic rod was placed in the splint, inferior to and parallel to the forearm, extending from the elbow (hinged on a support post) past the fingers to rest in a swivel cradle. The splint was supported from the ceiling on a pulley to minimize the weight the motor must pull and to allow the subjects to relax in the passive mode. The splint, rod, and supports were used in both active and passive modes to maintain similar response characteristics. If the subject was not passive, tension in the muscles resisting movement deactivated the decade counter, providing a check on the passivity of the subjects. Complete passivity was not necessary since Rabbitt (1968) demonstrated that rapid error corrections were specific to the correct response, not just to unrelated motor activity.

An active trial consisted of the presentation of a warning light of variable duration followed by one of the stimulus lights. The subject responded by flexing or extending the elbow to move the lever in the indicated direction as quickly as possible, correcting any errors immediately (Figure 2). A passive trial consisted of the presentation of the warning light of variable duration, followed by the stimulus light. After a constant delay (450 msec) the motor engaged the lever and moved it to the farthest extent in one direction in 250 msec, after which it returned to the home position in the same amount of time. On

trials where the experimenter wished to induce a "passive error" the lever moved in the direction opposite of the stimulus light (Figure 2).

Procedure. Subjects were familiarized with the apparatus and presented with the informed consent form explaining the experimental procedures. The subject was seated facing the lever with the right shoulder aligned with the lever. Movements to the left required biceps activation (elbow flexion) while movements to the right required triceps activation (elbow extension). Lights in the testing chamber were extinguished except for a small light to record data by. Subjects were advised and encouraged to respond as quickly as possible to minimize the occurrence of cautious strategies that eliminate errors altogether. Subjects were instructed to correct errors rapidly (see Appendix).

Each subject attended five 1 hour experimental sessions on five consecutive days. The first four sessions were occupied by one of the four combinations of efferent activity (active-passive) and anticipation (high-low), with the order of these conditions counterbalanced to prevent practice effects. Two levels of anticipation were achieved through manipulating stimulus expectancy on any one trial such that in the random condition the order of left and right stimuli was random, each equiprobable on any trial. In the high anticipation condition, a distinct, predictable pattern (L,R,L,R,L, etc.) determined the order of stimuli. The pattern

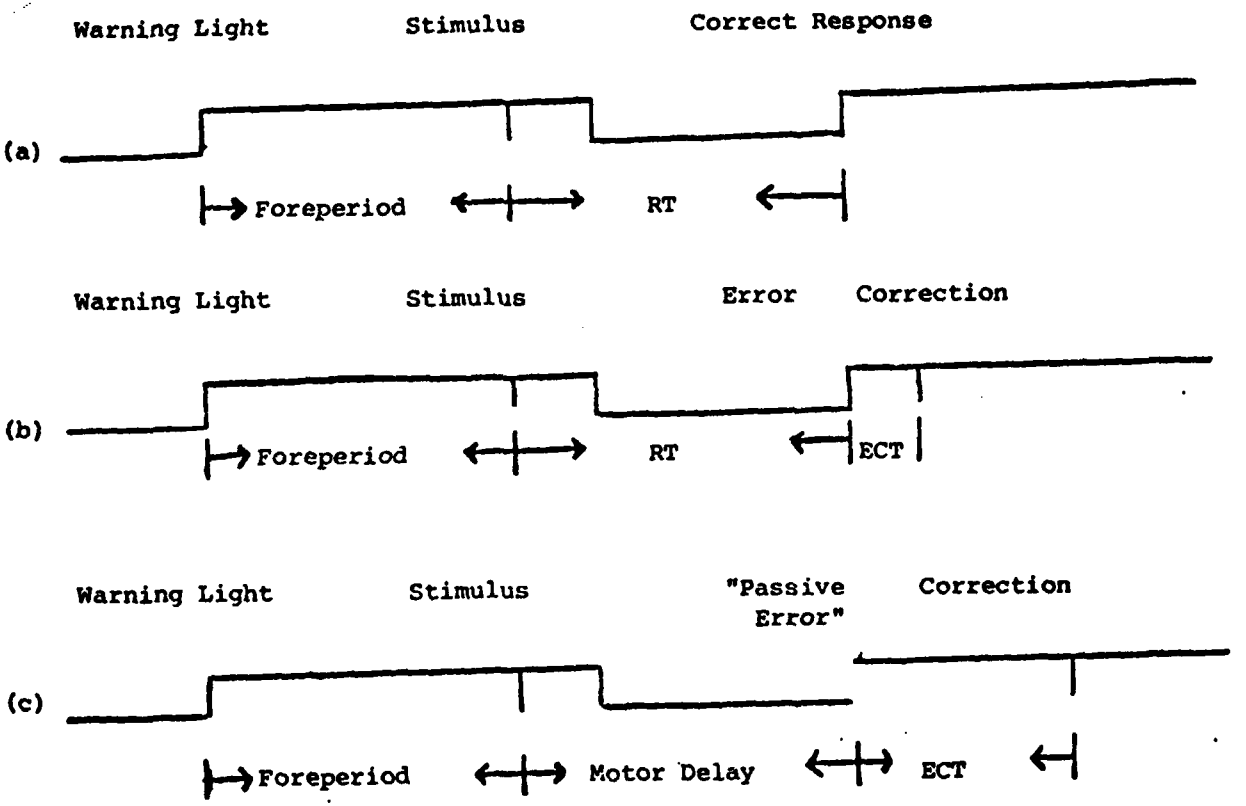



Figure 2. The events in a correct response (a), in an active error (b) generated by the subject, and a passive error (c) generated by the apparatus.

was valid on 90% of the trials, so that subjects knew in advance which stimulus to expect. On 10% of the trials, the pattern deviated, a manipulation analogous to the polarity reversals used in step tracking tasks (Angel, 1976. Angel & Higgins, 1969; Jaeger et al., 1979).

In the Active-Random condition, subjects actively performed a two choice response task in which the choice of left and right occurred with equal probability and in a random order. The Active-Patterned condition required subjects to respond as in the Active-Random condition, but high anticipation was induced by the regularity of the pattern of stimuli presentation. In the Passive-Random condition subjects monitored the stimulus display and were moved passively as described previously. No overt response was required unless the lever went in the wrong direction ("passive error"). The subject was instructed to correct any "errors" as quickly as possible. Left and right stimuli occurred with equal probability and in a random order. The Passive-Patterned task was similar to the Passive-Random task with the exception that stimuli occurred in the alternating pattern, generating high anticipation. In the passive conditions, experimenter-induced errors (mismatches of stimulus and arm direction) occurred on 10% of the trials.

In the final session for all subjects, simple visual reaction times and choice proprioceptive reaction times were collected to provide appropriate control comparisons for the other choice

conditions. In the simple visual reaction task, subjects knew in advance which stimulus should be presented and responded as quickly as possible. In the choice proprioceptive task, the stimulus lights were blanked and subjects responded to the motion of the lever by moving in the opposite direction. Left and right movements of the lever occurred with equal probability and in a random order.

Correct RTs, error RTs, and ECTs were collected in each of the active conditions, but only ECTs could be recorded in the passive conditions. In addition to these dependent variables, Schmidt and Gordon's (1977) correction time (CT) was analyzed. Correct trials following error trials and reversals in the patterned condition were not included with other correct trials since it has been shown that subjects adopt a more cautious strategy immediately following errors and respond uncharacteristically slow (Rabbitt, 1966a)

Each session consisted of 220 trials of the specified experimental condition. The first 20 trials of each session were designated practice and warmup and were not included in any analysis. Rest periods were provided halfway through a testing session.

Design and Analysis. The experimental design was a repeated measures design such that all subjects performed in all conditions. Median scores in each dependent variable were calculated per

condition for each subject and submitted to analysis in a combination of repeated measures ANOVAs and *t* tests. Median values were used due to their insensitivities to extreme scores and large variances. Error rates were also examined per subject and per condition.

Results

The results are organized in two sections. The first reports the findings concerned with anticipation and includes analysis of error rates, RTs and CTs. The second reports the findings concerned with efferent activity and includes analysis of RTs and ECTs. Table 1 displays the average median values for all subjects in all conditions.

Anticipation. The anticipation hypothesis predicted higher error rates in the anticipation condition relative to the random condition. However when Active-Random and Active-Patterned error rates (Table 2) were compared, a paired *t* test revealed no differences in error rates, $t(11) = -.29$. Error rates in the passive condition were determined by the experimenter since the apparatus created passive errors, Passive error rates were set at 10% or 20 trials out of 200.

To establish that subjects were indeed making use of the high stimulus predictability of the Active-Patterned condition, reaction times of the 90% valid, correct trials were compared with simple visual reaction times (100% valid), by paired *t* test. The means of the individual median values for these two

Table 1

Means and Standard Deviations of Median Values

All Conditions, N = 12 Subjects

| Dependent Variables | | Correct RTS | Error RTs | Error Correction Times | Correction Times = RT + ECT |
|---|---|---|---|---|---|
| Active - Random | | 231 (12) | 245 (26) | 71 (14) | 318 (33) |
| Active - Patterned | 214* (18) | 322 (43) | 294 (45) | 97 (27) | 395 (38) |
| Passive - Random | | | | 236 (44) | |
| Passive - Patterned | | | | 212 (31) | |
| Control Comparisons | | Simple Visual RT = 214 (14) | | Choice Proprioceptive RT = 182 (23) | |

*Correct RTs on the trials where the pattern was 90% valid, remainder of scores in this condition represent the 10% of the trials where the pattern was invalid.

( ) indicate standard deviations.

Table 2

Individual Error Rates in % of Trials

Active Conditions

| Subject # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Low Anticipation (Random) | 2.5 | 4.0 | 6.0 | 3.0 | 4.0 | 1.0 | 8.0 | 5.5 | 5.0 | 1.0 | 1.5 | 4.5 | 3.83 |
| High Anticipation (Patterned) | 3.5 | 2.0 | 2.0 | 5.0 | 7.0 | 2.0 | 4.5 | 5.0 | 4.5 | 2.5 | 6.0 | 4.5 | 4.04 |

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UNCLASSIFIED 10 AFOSR-TR-82-0620 NL



conditions were identical ($\bar{X}$ = 214 msec) and the $t$ value was not significant. These means and standard deviations are also included in Table 1.

A 2 x 2 repeated measures ANOVA was performed on the reaction times of the active condition, comparing correct and error responses under the two levels of anticipation. In this analysis the correct and error trials under the high anticipation (patterned) condition are those 10% of the trials in which the stimulus pattern deviated. Thus, these trials represent the low probability trials of the high anticipation condition. The main effect of anticipation on RTs was significant, $F(1,11) = 81.57$, $p<.001$. The RTs of the random condition ($\bar{X}$ = 238 msec) where stimulus probability was 50% were shorter than the RTs of the patterned condition ($\bar{X}$ = 308 msec) with stimulus probability of 10%. Surprisingly, error trials ($\bar{X}$ = 270 msec) did not differ from correct trial ($\bar{X}$ = 277 msec), either in a main effect or under either level of anticipation. In previous choice reaction tasks, error responses have been shown to have shorter RTs than correct trials when stimulus probabilities are equal (Megaw, 1972; Hale, 1969; Ollman, 1966; Yellot, 1967) and slower RTs if they occurred on improbable trials (Gibbs, 1965). Such differences did not occur here. Figure 3 shows that the only significant difference was the common finding that RTs to improbable stimuli are slower than RTs to equiprobable stimuli (Gibbs, 1965; Theios, 1977).

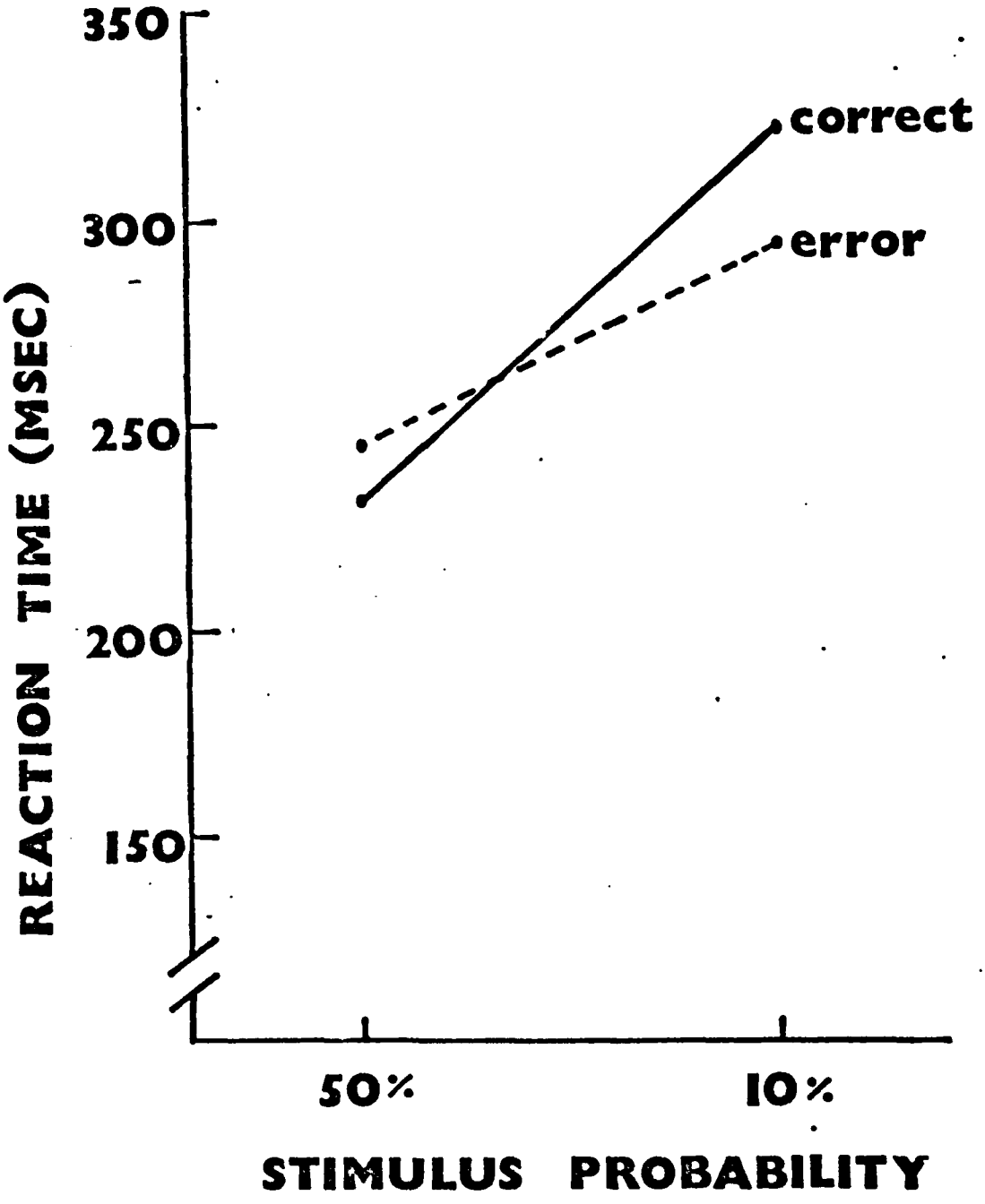



Figure 3. Mean reaction times of correct and error responses under two levels of stimulus probability (anticipation).

The composite score, CT, recommended by Schmidt and Gordon (1977), was analyzed for anticipation effects. The anticipation hypothesis predicted no differences in CT. Since this dependent variable could only be collected in the active case, a paired *t* test was performed on the CTs from the Active-Random and Active-Patterned conditions. The Active-Random CTs ($\bar{X}$ = 318 msec) were significantly shorter than the Active-Patterned CTs ($\bar{X}$ = 395 msec), $t(11) = 4.44$, $p < .001$. This composite score reflected the anticipation main effect found in RTs; subjects respond to improbable stimuli slower than to equiprobable stimuli.

Efferent Activity. Important comparisons for the internal monitoring of efference notion revolved around the active-passive manipulation. The first comparisons answer whether the rapid error corrections were actually "rapid." In past investigations classification of an error correction as "rapid" was predicated on the ECT being shorter than a simple RT (Angel, 1976; Angel & Higgins, 1969; Higgins & Angel, 1970; Jaeger et al., 1979). To demonstrate this difference a paired *t* test was performed on data from the simple visual RTs and the Active-Random ECTs. The *t* test revealed that the simple visual RTs ($\bar{X}$ = 214 msec) were significantly longer than the Active-Random ECTs, ($\bar{X}$ = 71 msec), $t(11) = 26.14$, $p < .001$. The means and standard deviations are also included in Table 1.

The comparison critical to this experiment is found in the effect of anticipation and the presence of efference on ECTs. A

2 x 2 repeated measures ANOVA was performed on active and passive error corrections under two levels of stimulus probability (Anticipation). The meain effect of efferent activity (active, $\bar{X}$ = 84 msec, versus passive, $\bar{X}$ = 224 msec, error corrections) was significant, $F(1,11) = 148.25$, $p<.001$, with active, self-generated errors being corrected in much briefer times than passive, externally-induced errors. The main effect of anticipation was not significant (low anticipation $\bar{X}$ = 153.5 msec, high anticipation $\bar{X}$ = 154.5), but the interaction of anticipation and efferent activity was significant, $F(1,11) = 17.56$, $p<.01$. As can be seen in Figure 4, the significant interaction was due to anticipation having small but opposite effects on the active and passive error corrections.

The argument could be made in the passive conditions that subjects responsed slower because they were not required to respond on every trial. That is, they would not be in a "set" to respond and could be lulled into a state of relaxed vigilance. Instructions to subjects warned of this possibility. In addition, a second control condition was collected to determine the possible magnitude of this effect. A choice proprioceptive task was administered, in which subjects responded to the movement of the lever (and thereby their arms) by reversing its direction. Other than a warning light, no visual information was provided. The probability of the two stimuli (left and right) was equal on any trial, and the order of left and right movement stimuli was random across

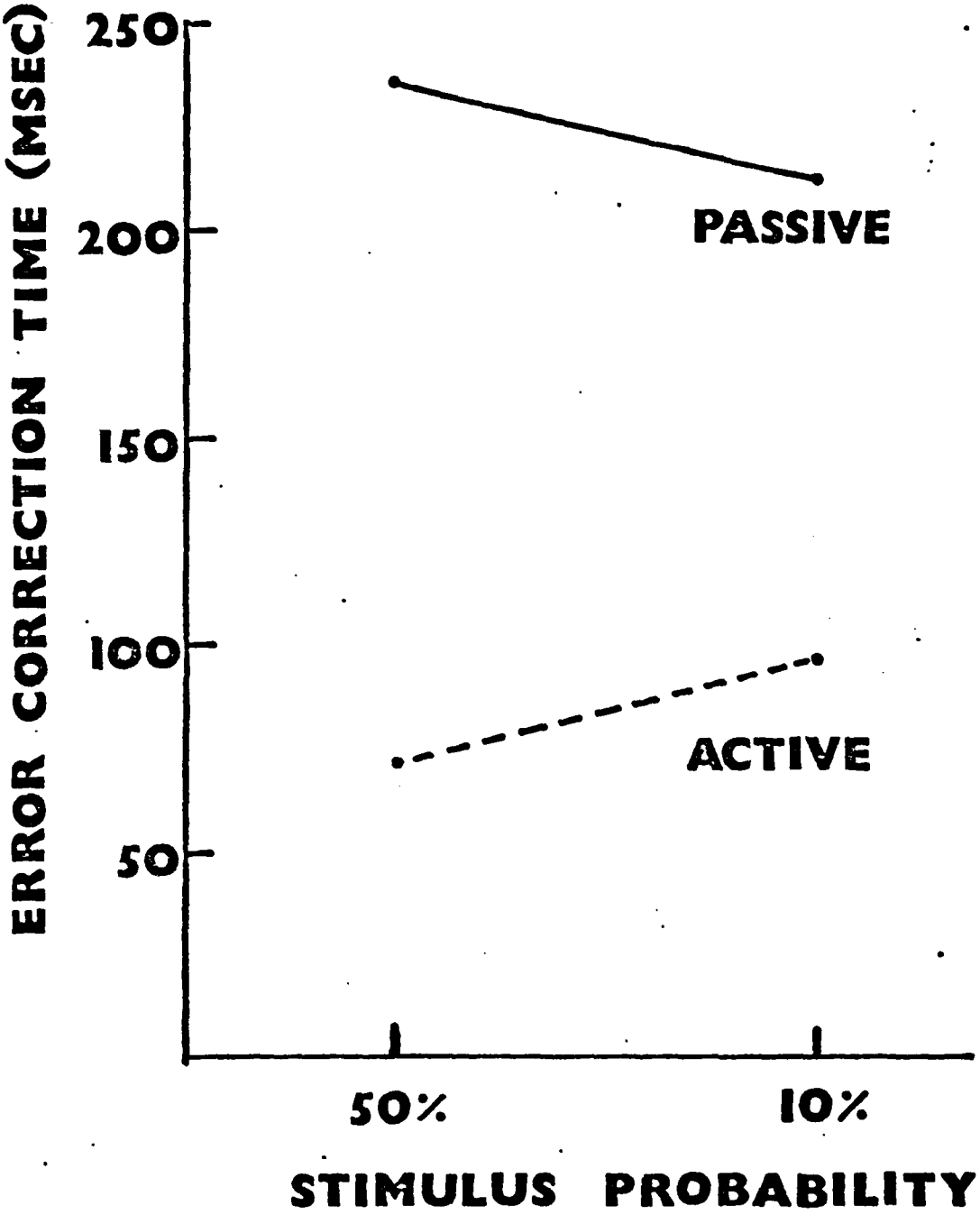



Figure 4. Mean error correction times for active and passive error corrections under two levels of stimulus probability (anticipation).

the condition. To determine if this effect was present, a paired *t* test was performed on the data of these two conditions. The choice proprioceptive RTs ($\bar{X}$ - 182 msec) were significantly faster than the ECTs of the Passive-Random condition ($\bar{X}$ = 236 msec), $t(11) = 5.21$, $p < .001$. Means and standard deviations for these conditions are presented in Table 1.

## Discussion

The primary intent of this experiment was to determine whether anticipation or internal feedback was responsible for rapid error corrections. Creating experimental anticipation increased correct RTs, error RTs and CTs on improbable trials, but had no effect on ECTs. That anticipation would affect these dependent measures is expected since the RT component of the movement is sensitive to stimulus probability. Only the removal of the efferent signal responsible for the error succeeded in elevating ECTs. This discussion will focus first on anticipation and finally on internal monitoring of efference.

It must be established for the present experiment that subjects were anticipating the stimulus presentation in the Active-Patterned condition. Two findings substantiate this requirement. First, RTs for those trials of the Active-Patterned condition in which the stimulus pattern was 90% valid should have been very similar to RTs in the simple visual RT task (100% valid). The means for these two conditions were in fact equal, indicating that subjects were making use of the stimulus pattern to benefit response preparation. Second, the main effect of anticipation on RTs showed that the 10% reversal or improbable trials of the Active-Patterned condition were significantly longer than the RTs of the Random condition. Not surprisingly, this same effect was

reflected in the composite score, CT. It is indicative of the cost incurred on improbable trials in order to anticipate (Larish, 1979; Posner & Snyder, 1975).

Critical to the false anticipation hypothesis is the supposition that anticipation is responsible for errors. Schmidt and Gordon's (1977) evidence of this was higher error rates in the anticipation condition. However, they calculated error rates in the anticipation condition differently than in the random condition. Instead of dividing the number of errors by the total number of trials, they divided only by the total number of stimulus reversal trials in the patterned condition to get an extremely high error rate of 64%. If the error rate for this condition is calculated as in the random condition, dividing by the total number of trials, it amounts to only 4%, actually less than the random condition of 8%. In the present experiment error rates did not differ with anticipation levels, indicating that the frequency of errors may be unrelated to anticipation levels.

Another indication that anticipation was responsible for rapid error corrections would be the presence of the classical speed-accuracy tradeoff (Egeth & Smith, 1967; Hale, 1969; Megaw, 1972). In discrete choice response tasks, this tradeoff appears as error reaction times which are faster than correct reaction times (when stimulus probabilities are equal). In the present experiment, there were no differences between correct and error responses for

either of the active conditions (a finding also true in the Schmidt and Gordon study). Thus, anticipation did not result in a speed-accuracy tradeoff, either in terms of number of errors or fast error responses.

The anticipation hypothesis would also predict that CTs would be equal between random and patterned conditions, since it represents in all errors a stable psychological refractory period and a simple reaction time. However, in the present experiment CTs were significantly longer in the anticipation condition, ($\overline{X}$ = 395 msec) than in the random condition ($\overline{X}$ = 318 msec). Errors in the patterned condition occurred on improbable stimuli; RTs reflected this low expectancy, as of course did CTs. The rationale applied in the anticipation hypothesis stated that should the temporal characteristics of errors elicited under anticipation resemble those generated in the random condition, then the same mechanism, anticipation, was responsible. Different temporal patterns were elicited from the two levels of anticipation in the present study, failing to support the anticipation hypothesis.

The variable CT hypothetically represents a simple RT plus a psychological refractory period according to the anticipation hypothesis. The criterion used to determine whether CTs represented the sum of these hypothetical periods was to be greater than a simple RT. Applying this criterion in the present experiment, all RTs other than the 90%-valid RTs of the Active-Patterned condition would qualify. Additionally, if the Active-Patterned CT equals

395 msec (Table 6) and a simple RT in this experiment equals 214 msec, then the psychological refractory period proposed to comprise the remainder of the CT is around 180 msec, an excessive figure for a psychological refractory period (Gottsdanker, 1980; Kantowitz, 1974).

One additional point should be made regarding the anticipation hypothesis and Schmidt and Gordon's (1977) explanation of CTs. Schmidt and Gordon (1977) contended that errors occur due to spatial anticipation of one of two targets. Because the subject has anticipated, the latency of the error is briefer than one RT. The erroneous anticipation is detected by the subject at the time the stimulus comes on and does not match the subject's expectancies. Since there is already a response in progress, the corrective response latency cannot begin until a psychological refractory period has elapsed. And, since the subject has anticipated one of the possible responses, the choice of corrective responses is effectively reduced to one. There is, following the psychological refractory period, a simple RT that precedes the reversal of the initial incorrect response. This explanation of temporal events does not appear to allow any time for comparison of the actual stimulus with the expected stimulus. This error detection stage has not been allocated any processing time; thus, the CT as calculated by Schmidt and Gordon (1977) appears to be too brief to encompass a psychological refractory period, a simple RT, and

an error detection stage of the type described.

The anticipation hypothesis does not seem to be an adequate explanation of rapid error corrections considering the present findings. It is entirely possible that anticipation may be present and may contribute to the genesis of an error, i.e. the subject guesses wrong. The cause of an error may not be related to the mechanism responsible for its correction; the global goal of the present study was to speculate on the nature of this mechanism.

The manipulation unique to this experiment was the use of a passive error correction task. Crossing this manipulation of efferent activity with stimulus probabilities, allowed one to determine whether anticipation or efference was responsible for rapid error corrections. The removal of efferent activity was successful in altering ECTs where many other variables -- compatibility (Angel, 1976), anticipation (Schmidt & Gordon, 1977), vibration (Jaeger et al., 1979), etc. -- had not. This finding was seen in a very large difference between active and passive ECTs in the magnitude of 140 msec (in the random case, this difference was 165 msec). Anticipation, when averaged across active and passive conditions made only a 1 msec difference. In examining the interaction (Figure 4), anticipation was seen to have an effect on passive ECTs opposite that on active ECTs, benefitting the passive mode (24 msec) and decrementing the active mode (18 msec). Finding opposite effects of the same variable is another indication

that different mechanisms are operating in the two tasks.

In the ECTs it seems clear that subjects can rapidly correct their own errors, that is, internally generated errors accompanied by appropriate efferent activity. However, when the error is externally generated, detectable only in the afferent information, rapid error corrections do not occur. Instead, ECTs approximate normal RTs and display the expected RT decrease from high stimulus probability (Figure 4).

The active-passive comparison discussed here must be qualified. As stated previously, there are differences between active and passive movement which should not be interpreted as some benefit of internal feedback. The sensitivity of the muscle spindles differs between active and passive movement (Granit, 1975, Hagbarth & Vallbo, 1968; Hagbarth, Wallin & Löfstedt, 1975; Vallbo, 1973). In active movement the intrafusal muscle, via gamma activation, adjusts the length of the spindle to maintain its firing as the extrafusal muscle changes length via alpha activation. Gamma drive to the intrafusal fibers is absent in passive movement and the activity of the spindles is phasic (Hagbarth & Vallbo, 1968; Vallbo, 1973) yielding periods of diminished sensitivity. However, the diminished sensitivity can account for no more than 25 - 30 msec of the active-passive difference (Conrad, Matsunami, Meyer-Lohmann, Wiesendanger & Brooks, 1973; Vilis, Hore, Meyer-Lohmann & Brooks, 1976). Of

the 165 msec difference between active and passive ECTs, reduced spindle sensitivity can explain approximately 30 msec, leaving a 135 msec advantage to the active case.

As mentioned previously, the argument could be made that in the passive conditions subjects respond slower because they were not required to respond on every trial. The subjects may not have had a "set" to respond on every trial, and perhaps might be inattentive or relaxed. The choice proprioceptive RTs were collected as a control comparison to determine the magnitude of this "set". Subjects responded in a choice paradigm to the movement of the lever by reversing its direction. The condition closest to this control with respect to task and processing demands was the Passive-Random condition. In this condition, subjects also responded to the lever direction and the order of stimulus presentation was random. However, subjects in the Passive-Random condition had the additional task of comparing the proprioceptive input from the lever to the visual stimulus information they had received 450 msec earlier.

Two processing differences exist between the passive-random and choice proprioceptive conditions: the probability of responding ("set") and the additional stimulus comparison task. The latter process must also take place in the active error correction and should not be excluded from the active-passive difference. However, since the 54 msec difference between the control and Passive-Random

conditions inextricably combines these two processes; let it represent conservative estimate of "set" to respond. Thus, the lack of a "set" to respond can explain at the most, 54 msec of the active-passive difference.

An 80 msec advantage to active error correction remains which appears inexplicable except by some benefit of internal information. However, another peripheral source of error information is available and could achieve the error correction in the brief time thought by many to exclude peripheral sources (Angel, 1976; Jaeger et al., 1979; Megaw, 1972). Recently, it has been established that spondle activity can be coincident with the onset of muscle activity (Vallbo, 1973; Hulliger, Nordh & Vallbo, 1979). Since muscle activity normally precedes movement by 40 to 70 msec (Brown & Cooke, in press; Corser, 1974), and spindle activity is nearly coincident with its onset, it is possible that the spindle afference from the incorrect muscle communicates error information. Even in the briefest error correction times (30 msec), the latency from onset of muscle activity to the correction is well within the range of a triggered reaction time (Evarts & Tanji, 1976) or in some studies a voluntary RT to proprioceptive stimuli (Hufschmidt & Hufschmidt, 1954; Luschei, Saslow, & Glickstein, 1967). This possibility weakens the argument that the 80 msec advantage found in correcting active errors is attributable only to central monitoring of efference. The present investigation did not eliminate this possibility.

With this qualifying statement in mind the following

conclusions were made:

1. The false anticipation hypothesis of Schmidt and Gordon (1977) is not a viable alternative explanation to internal efferent monitoring.
2. Although anticipation may be related to the cause of some errors, it does not appear to explain either the frequency of errors or their rapid correction.
3. Passively induced errors of elbow flexion and extension cannot be corrected as rapidly as actively (subject) generated errors. In actively generated errors, the efferent activity associated with the error appears necessary and sufficient to detect and rapidly correct the error, although the afference associated with this activity may conceivably signal an error. In passively induced errors where the apparatus creates the error, error detection must rely on afferent information. The preferred explanation is that errors which are internally generated may be monitored via some central monitor which is responsible for the corrective response soon after the error. Errors which are externally generated do not possess the internal efference which may supply rapid error information.

The rationale for Experiment 1 was derived from the central monitoring of efference theory, stating that removal of efference

would also remove the source of early error information and prevent rapid error corrections (Festinger & Cannon, 1965; Jones, 1974; Pardew, 1974; Taub & Berman, 1968). The active-passive manipulation of Experiment 1 was successful in altering the ECTs as predicted. Based on this theory, another variable that would be expected to affect ECTs would be the length and structure of the efferent command. A long or complicated command would be predicted to require longer monitoring time to detect the error. Experiment 2 attempted to test this hypothesis by altering the complexity of the movement responses.

On further inspection of ECTs, their distribution (containing all error trials) appeared to be quite skewed with a mean of 89 msec and a median and mode of 68 msec. At least 20% of the ECTs were between 30 and 50 msec in duration. Normally, electromyographic activity associated with movement precedes displacement by approximately 40 to 70 msec (Brown & Cooke, in press; Corser, 1974; Hathaway, 1935). Since ECTs represent the period from initiation of the error to the corrective reversal, the muscular activity responsible for the corrective reversal must have preceded the initial incorrect movement. Such a finding would make the periphery an unlikely source of error information. Experiment 2 examined the EMG activity of correct and error trials for any evidence of error-correcting muscle activity that preceded movement.

## Experiment II

In the past, attempts to modify the processing of the efferent signal in a rapid error correction paradigm have consisted of: reversing stimulus-response compatibility (Angel & Higgins, 1969; Higgins & Angel, 1969; Jaeger et al., 1979; Gibbs, 1965; Rabbitt & Phillips, 1967); increasing the number of choices of possible responses (Rabbitt, 1966a); altering the type of corrective response, (Rabbitt, 1968); and manipulating expectancy (Gibbs, 1965; Schmidt & Gordon, 1977). These factors are all known to affect stages of information processing involved in preparing for movement (Massaro, 1975; Sternberg, 1969; Theios, 1977 and thereby RT. However, these variables have been shown not to affect ECTs, that time period proposed to represent the time required to monitor an efferent command. Since the responses used in these previous studies have always been equated in terms of movement complexity, then no differences in monitoring time would be expected. Movement complexity refers to the number of muscle groups and directional changes required in the movement (Hayes & Marteniuk, 1976; Henry & Rogers, 1960; Sternberg et al., 1978). In studies where these variables are manipulated, simple RTs are seen to increase as a function of additional response elements (muscles, direction changes). This complexity is assumed to be reflected in the efferent command, since it represents the degree of structural organization of the effector units within the central nervous system

(Hayes & Marteniuk, 1976).

If alternative responses differ along this dimension of complexity in a choice response task, then internal monitoring of the commands would have different times. On error trials, one would predict ECTs to vary with the complexity of the movement. In Experiment 2, two responses of unequal complexity were used in a choice reaction paradigm. The relative complexity of the responses was determined in a simple reaction task, such that the high complexity task had a longer RT than the low complexity task for each subject. Then the two tasks were combined in a choice condition and balanced for possible directional biases (for half the subjects the high complexity task required extension of the elbow to the right, for the other half this task required flexion, although Corser 1974, found no differences in the RTs of elbow flexion and extension). An error in the direction of the high complexity task would increase the error correction time relative to errors in the direction of the low complexity task, since a high complexity task is being initially programmed and monitored. The effect of combining responses of differing complexity in a choice condition has not been previously demonstrated. Experiment 2 provided information on this comparison; but one may speculate that these complexity differences may also be seen in choice reaction times.

A second purpose of Experiment 2 was examination of EMG records from correct and error tirals. As mentioned previously,

Experiment 1 data included a number of brief ECTs (20% of ECTs between 30 and 50 msec). Given a latency of 40 to 70 msec between onset of EMG activity and onset of movement (Brown & Cooke, in press; Corser, 1974 Hathaway, 1935), it seems likely that the muscular activity responsible for the correction should have preceded the initial error movement in these very brief error corrections. Previous research that included EMG records did not report such findings (Jaeger et al., 1979; Megaw, 1972), although Megaw did note an increase in amplitude and frequency of the corrective agonist when errors occurred. In these studies, the results reported are terse and not very informative; it is not clear whether this aspect of the data (early EMG activity) was attended to. Therefore, an analysis of EMG records of error responses and average correct responses was included in Experiment 2.

Method

Subjects. Eight, right-handed, male volunteers from the University of Western Ontario served as subjects.

Apparatus. Subjects were seated, facing the stimulus display on a cathode ray oscilloscope, 1 meter in front of them. Subjects grasped a manipulandum handle with the forearm supported at the elbow, adjacent and right of the right shoulder. The arm was positioned so that the elbow was beneath the pivot point of the manipulandum. A precision potentiometer mounted to the axis of rotation was used to monitor handle, and therefore forearm, position. Angular velocity of handle movement was derived from a small DC

torque motor and was used to stop a digital clock when velocity deviated from 0. RTs for all responses were recorded from this digital clock. For a more detailed description of this apparatus see Thomas, Craft and Brooks (1976).

Subjects were required to make step tracking movements in response to movement of a thick, vertical bar on the oscilloscope (see Figure 5). In the neutral position the target was positioned in the center of the screen. In the low complexity task, the target appeared to the left, 3 cm or to the right 3 cm, (left for half the subjects, right for the other half). In the high complexity task, two targets appeared simultaneously to the left, 2 and 3 cm respectively or similary to the right for the other half of the subjects. The targets were not bound by mechanical stops and appeared after variable foreperiods of .5, 1.0 and 2.0 sec.

The angular position and surface electromyograms from biceps and the lateral head of the triceps using surface disk electrodes (.8 cm in diameter, spaced 4-5 cm apart) were recorded. EMGs were filtered (low frequency cut-off = 20 Hz, high frequency cut-off = 2000 Hz) and full wave rectified before recording. Data were digitized online with an effective sampling rate of 500 Hz, collected on disk and transferred to magnetic tape. From the digitized data, averages of correct responses for each task and foreperiod were generated, averaging around the point on the position trace where the slope changed from 0. Plots of each average and all error traces were obtained for later analysis.

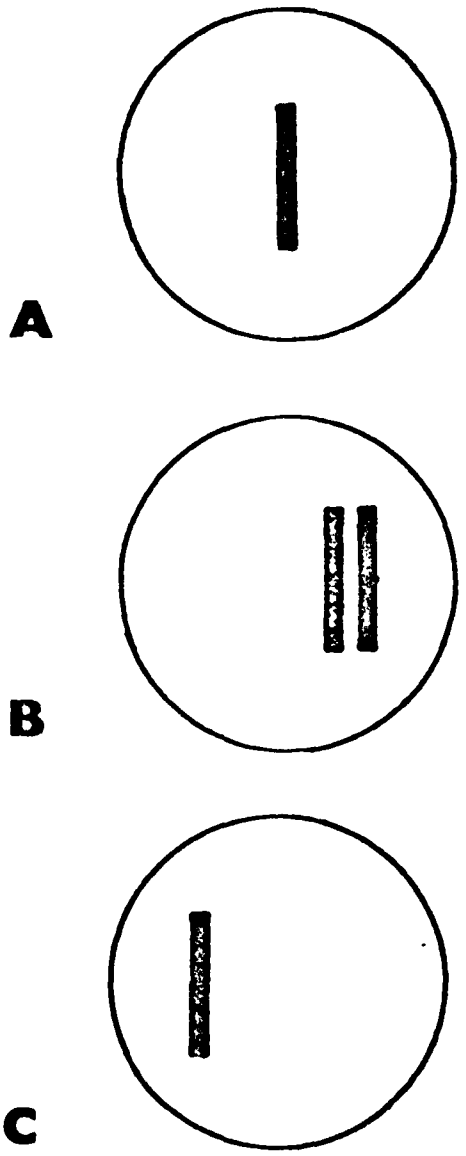



Figure 5. The three possible stimulus displays: A. neutral position displayed between trials, B. high complexity target, C. low complexity target.

Procedure. Subjects were familiarized with the apparatus and given experimental instructions along with informed consent forms. Each subject was then seated comfortably in the apparatus chair and wired with electrodes. All subjects received two experimental conditions, a simple RT and a choice RT task, lasting approximately 1 1/2 hours. In both experimental conditions, subjects received immediate knowledge of results regarding their RTs on each trial.

Two responses of differing complexity were used. The low complexity task required the subject to move from the center position to a single target to the side and hold. The complexity of the second response was increased by including two direction reversals. In the task, the subject was required to move from the center position to the far bar of the double target, reverse direction back to the near target, reverse again to the far target and hold. The experimenter monitored handle position on an oscilloscope to monitor accuracy. Subjects were provided with qualitative feedback regarding the incidence of target over- and undershooting.

In the simple RT condition, subjects received 20 trials of practice on each response prior to the beginning of testing. Fifty trials of each response were recorded. Half the subjects received the low complexity task first and half received the high complexity task first. To continue in the experiment subjects had to demonstrate a difference in RT between the high and low complexity task. Subjects were not informed of this criteria and only one subject was rejected.

In the choice RT condition, the two responses were combined in a two choice paradigm. The order of stimulus presentation was random, with both stimuli occurring an equal number of times. Subjects were advised to and encouraged to respond as quickly as possible to minimize cautious strategies that might eliminate errors. They were directed to correct any errors that did occur as rapidly as possible and to maintain spatial accuracy, as it was being monitored by the experimenter. For half the subject the low complexity task was performed with a flexion movement and the high complexity task was performed with an extension movement. The reverse was true for the other half of the subjects. The direction of the two responses was maintained throughout the two conditions for each subject. Subjects received 20 practice trials of each response, followed by 200 test trials with a rest break midway. Recording of position and EMG activity took place only in the choice condition due to space limitation.

Design and Analysis. RTs from the velocity activated digital clock and ECTs measured from individual error plots were analyzed in a combination of repeated measures ANOVAS and paired *t* tests. These analyses were performed on the median values for each subject. The incidence of errors for each task was also examined. The final analysis is a qualitative analysis of the obtained EMG records, comparing error responses with appropriate averaged correct responses.

## Results

The results are organized in four sections. The first briefly reports error rates. The second and third sections report the analysis of response latencies, including RTs and ECTs. The fourth section analyzes the EMG records obtained.

Error Rates. Errors occurred only in the choice condition. When subjects were presented with a low complexity stimulus but made an error toward the high complexity task the mean error rate was 2.81%. When subjects were presented with a high complexity stimulus but made an error toward the low complexity task the mean error rate was 2.06%. These error rates did not differ statistically, $t$ (7) = 1.09. Individual error rates for each subject by task are presented in Table 4.

Reaction Time Analysis. A 2 x 2 repeated measures ANOVA was performed on the RTs of the low and high complexity tasks as they occurred in the simple (no choice) and choice conditions. The simple and choice conditions also represent two levels of stimulus probability, 100% in the simple condition and 50% in the choice condition. It was expected that the two tasks differing in complexity would differ in a simple RT condition (Henry & Rogers, 1960; Sternberg et al., 1978); the outcome of the choice condition was not so predictable. Whether the introduction of a choice or response selection stage would equate the two tasks was in question. Only correct responses from the choice condition were included since only correct responses occurred in the simple

Table 3

Individual Error Rates in % of Trials

Choice Condition

| Subject # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | Mean |
|---|---|---|---|---|---|---|---|---|---|
| Low Complexity | 0.5 | 0.5 | 2.0 | 2.0 | 4.5 | 6.0 | 7.0 | 0.0 | 2.81 |
| High Complexity | 1.0 | 1.0 | 1.5 | 1.5 | 1.5 | 5.0 | 3.0 | 2.0 | 2.06 |

RT condition. The means and standard deviations are included in Table 5.

The main effect of task complexity was significant, $\underline{F}(1,7) = 14.75$, $\underline{P} < .01$, with the high complexity task requiring longer RTs ($\overline{X}$ = 314.8 msec) than the low complexity task ($\overline{X}$ = 239.5 msec). The main effect of choice condition was also significant, $\underline{F}(1,7) = 10.0$, $p < .02$, with the choice RTs being longer ($\overline{X}$ = 288.2 msec) than the simple RTs ($\overline{X}$ = 266.2 msec). The interaction of these two variables was not significant, $\underline{F}(1,7) = .34$, indicative of additivity and independence in the Sternbergian sense (Sternberg, 1968) (See Figure 6).

A second 2 x 2 repeated measures ANOVA was performed on the choice condition RTs only, comparing correct and error responses under the two levels of complexity. Error trials are designated low or high complexity according to the stimulus delivered, not the type of error committed. The result is that errors designated under low complexity were in the direction of the high complexity task, but were eventually reversed; the reverse is true of errors designated as high complexity. The means and standard deviations are included in Table 5 also.

Neither of the main effects were significant, however the interaction was significant, $\underline{F}(1,7) = 12.43$, $p < .01$, and is illustrated in Figure 7. On error trials when a low complexity stimulus was presented and the subject began to execute a task of high complexity, the RTs were of the same magnitude as the

TABLE 4

Means and Standard Deviations in Msec

RTs and ECTs

| Dependent Variable | Simple RT | Choice RT | | ECT |
|---|---|---|---|---|
| | | Correct | Error | |
| Low Complexity Task | 227.5 | 251.5 | 321.0 | 94.86 |
| | (22.4) | (24.9) | (25.2) | (12.8) |
| High Complexity Task | 304.8 | 324.8 | 284.3 | 92.58 |
| | (52.7) | (52.7) | (65) | (17.0) |

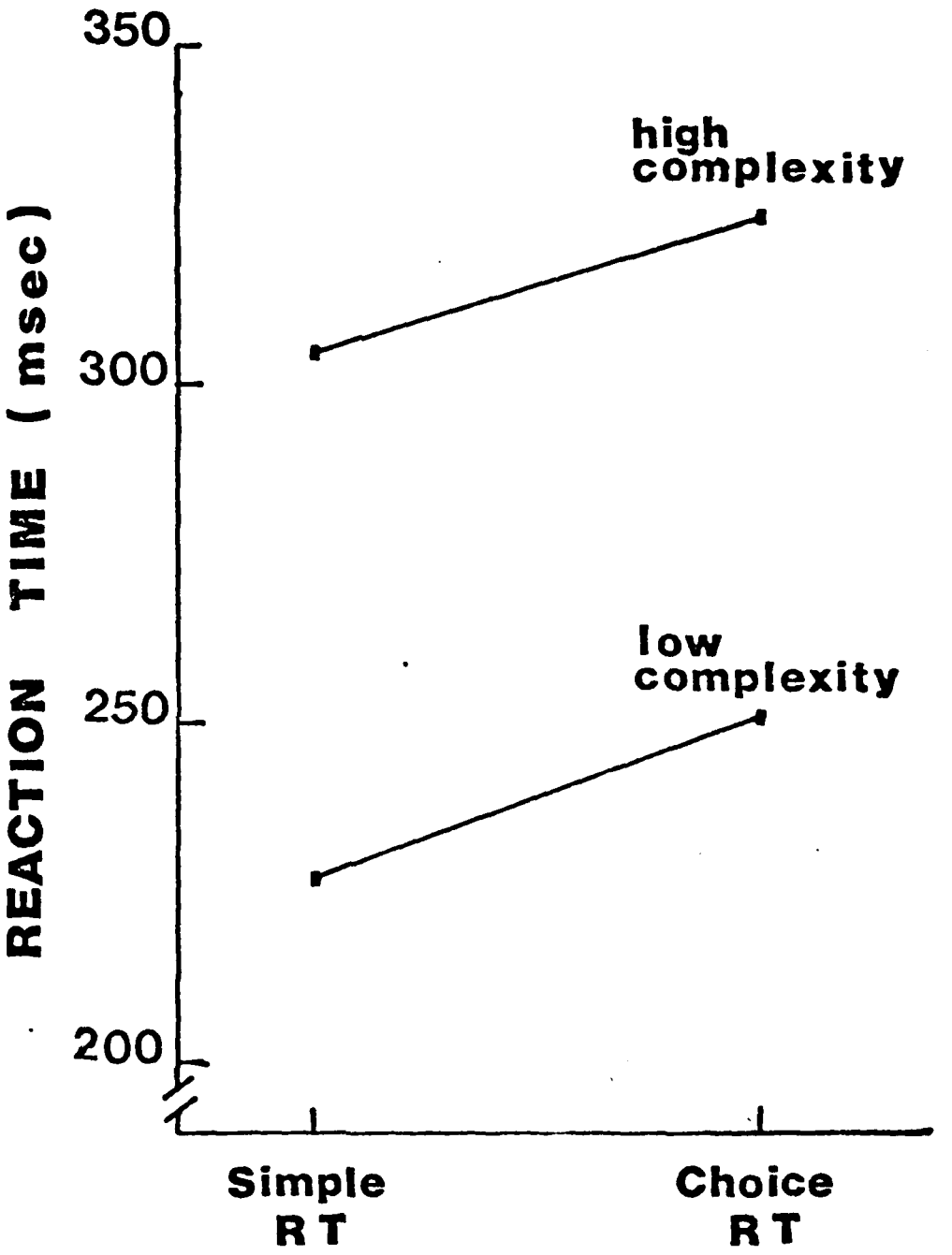



Figure 6. The effect of response complexity under simple and choice response conditions.

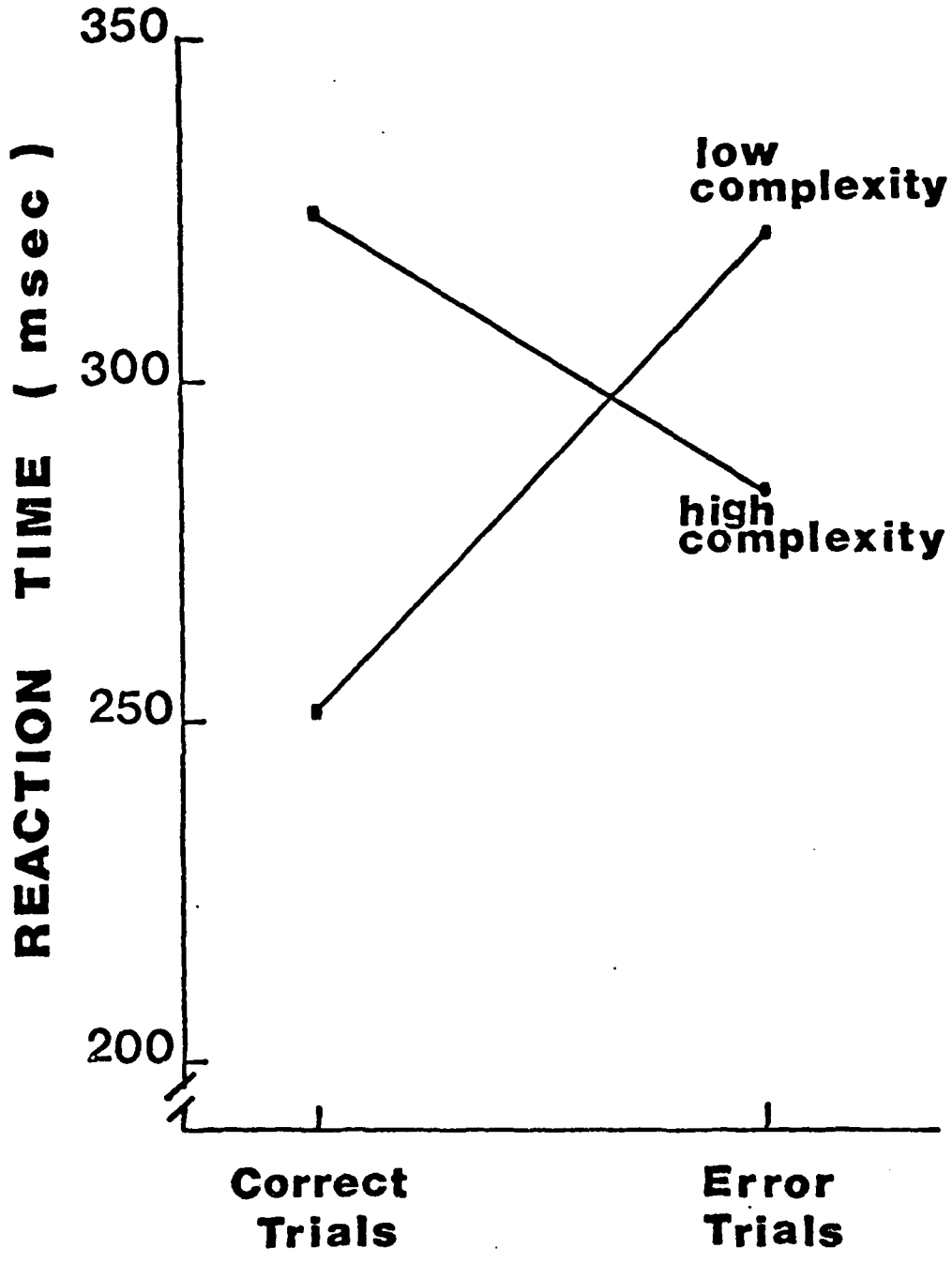



Figure 7. The effect of response complexity on correct and error trials.

correct-high complexity trials. The same is true of error trials when a high complexity stimulus was presented and a low complexity error was initiated, although to a lesser extent. This interaction indicated that subjects were indeed preparing the incorrect response, since their RTs were representative of the corresponding correct response. Figure 8 provides a better graphical representation of this error preparation, demonstrating the similarities between correct trials and the analogous error trials.

Error Correction Times. ECTs were measured directly from the position traces, from the inflection point marking the beginning of movement to the inflection point marking the reversal to the correct direction. It was suggested earlier, that if ECT represented the time required for an internal monitor to detect an error, then it should be sensitive to the efferent complexity of the motor command. However, when ECTs of low complexity ($\overline{X}$ = 94.8, SD = 12.8) were compared to ECTs of high complexity ($\overline{X}$ = 93.58, SD = 17.0), no difference was found, $t(6) = .25$. Task complexity, as manipulated here, appears to be yet another variable that affects RTs but not ECTs.

EMG Analysis. The intent of the EMG analysis was to examine agonist-antagonist onsets for differences in the patterns of error and correct trials. Previous EMG analysis of errors found no difference in agonist-antagonist onset times, only difference in amplitude and frequency (Megaw, 1972). However Megaw, compared

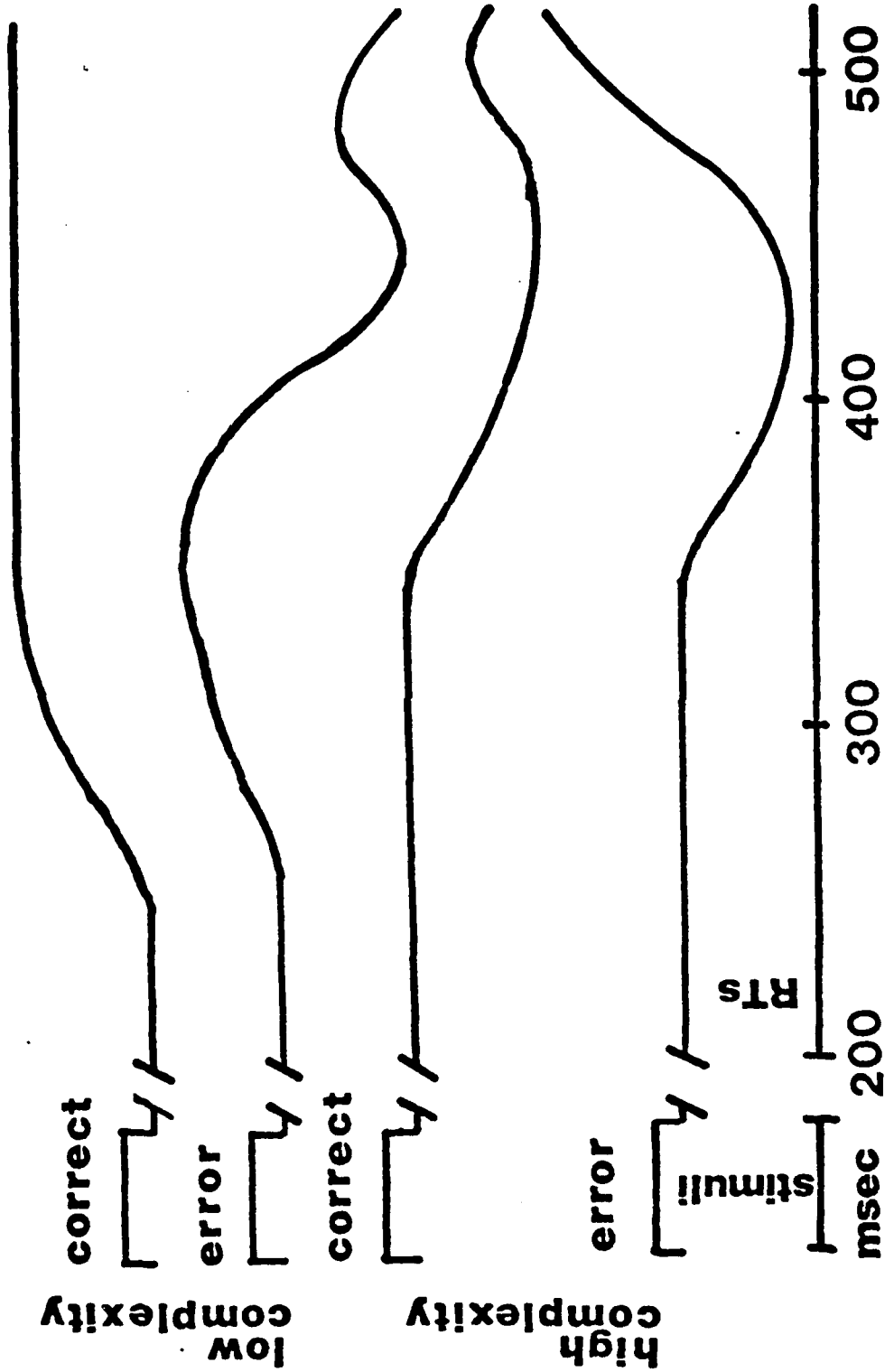



Figure 8. A temporal representation of the position traces derived from the interaction found in Figure 7. RTs were similar when subjects prepared a specific response (e.g. low complexity) whether correctly or in error.

flexion errors to correct extension movements instead of correct flexions. The present analysis made the latter comparison and found that at least on some trials, qualitative differences in the pattern of electrical activity existed. Additionally, the present analysis sought evidence in the EMG records that corrective activity may precede the incorrect movement.

EMG and position traces were plotted from magnetic tape using a computer plotting program. The reliable information contained in the individual plots was limited to: durations of electrical activity, relative onset of muscle activation or inhibitions, and the associated movement trace indicating the initiation, direction and termination of correct and error movements. Amplitude information was not reliable due to varying gain changes of the signal, during recording and plotting.

Error traces were superimposed on the appropriate correct average trace. The traces were oriented to each other relative to that point on the position trace where the slope changed from zero. This point represents the first sign of movement, either correctly or incorrectly. It is represented on each figure as the leftmost vertical line. The second line lies on the inflection point marking the direction reversal and termination of ECTs. In the early portion of the error traces (up to the reversal point) no differences between low complexity and high complexity tasks were distinguishable (See Figures 9 and 10). Any differences between these two tasks would not show up until

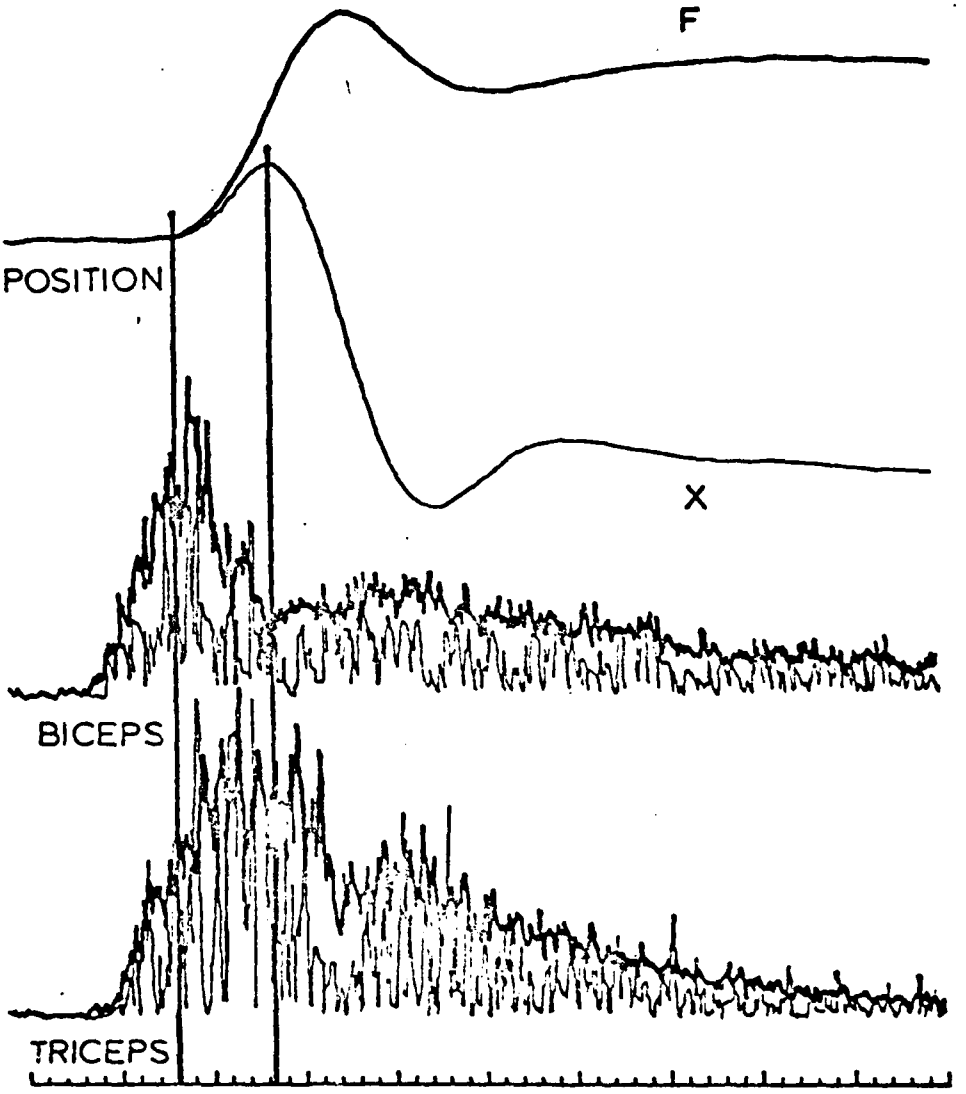



Figure 9. Error trace of subject B.M. The error was made toward the complex task toward flexion (F). Biceps is the agonist for the error and antagonist for the correction. EMGs do not show antagonist inhibition in biceps. Each time division is 20 msec.

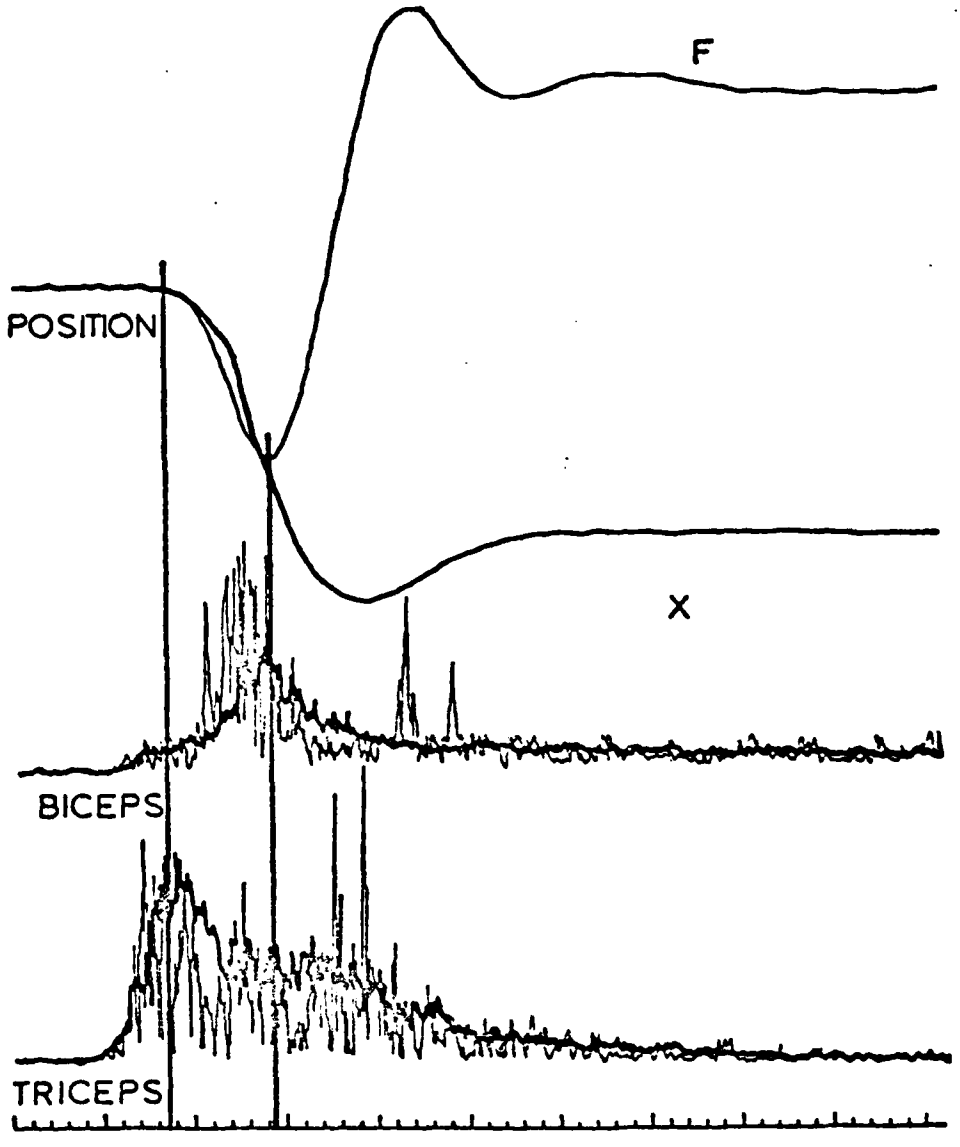



Figure 10. Error trace of subject P.M. The error was toward the simple task toward extension (X). Triceps is the agonist for the error and antagonist for the correction. EMGs do not show antagonist inhibition in the tricpes. Each division is 20 msec.

quite late in the trace, just prior to actual reversals in the complex task.

Next, attention was focused on the relative onsets of agonist and antagonist activity. Typical EMG patterns for fast movements are characterized by a triphasic pattern (Garland & Angel, 1971; Hallett, Shahani & Young, 1975a) in which a burst from the agonist is followed by a period of silence during which the antagonist is active. The antagonist becomes silent and the agonist active again. On error trials, the agonist responsible for the incorrect movement changes functional roles to become the antagonist for the correction. The same role reversal occurred for the error antagonist, it assumed the role of agonist for correction. The pattern of activity did not appear to change, only the functional roles of the component EMG bursts. However, some difference must exist since the error response eventually reversed to the correct direction. Logic suggested that perhaps the antagonist for the error (agonist for the correction) may become active sooner on error trials than on correct trials, arresting movement instead of simply decelerating. The correction would be achieved through early activation of the agonist. However, when error trials were superimposed on correct trials, (Figures 9, 10, 11 and 12), no differences were observed in these onset times.

In the introduction of this experiment, it was suggested that should the EMG activity of the agonist for the correction precede the

error, it would indicate an internal source for the error correction. However, it is not uncommon for the antagonist activity to slightly precede displacement (Angel, 1977). This temporal relationship occurred in many trials, both error and correct (See Figures 9, 10, 11, 12, 13). Since the antagonist for the error is also the agonist for the correction, no conclusions could be made regarding corrective EMG activity that preceded the error movement.

In determining where error responses deviated from correct responses, a distinct pattern of EMG activity was observed on approximately 40% of the error trials. On these trials, errors appeared to be corrected not by early onsets of the corrective agonist or by an increase in the activity of this muscle, but by inhibition of the muscle antagonistic to the correction (See Figures 11 and 12). On these errors, early activity of the correction's antagonist is responsible for the initial incorrect movement. Then, this muscle opposing the correction is inhibited while the corrective agonist is activated, and the movement reversal takes place. In the other 60% of the error trials it was not clear how the EMG activity related to the error correction, the agonist and antagonist were coactivated. Figures 9 and 10 show trials where an error was corrected, but the EMG record is equivocal with respect to the mechanism responsible. A frequency histogram illustrating the distribution of ECTs, sorted according to whether or not they

displayed the pattern of antagonistic inhibition and by complexity is presented in Figure 14. No frequency pattern was evident to indicate that the type of error (high or low complexity) or the presence of antagonist inhibition was related to the time to correct the error.

Although, no substantial evidence was found of corrective agonist activity prior to the error, there were several errors in which the inhibition of the corrective antagonist preceded the error. In 54% of those errors exhibiting the pattern of antagonistic inhibition, this inhibition preceded movements, by as much as 60 msec, (Figure 13). This finding seemed to contribute to the notion that rapid error corrections are a central phenomenon, since the correction can be seen even before the error has been made. However, the initial burst of the incorrect agonist may have produced peripheral error information from spindle receptors in that muscle, since fusimotor activity is present shortly after muscle activation (Hulliger, Nordh & Vallbo, 1979). The mean duration of the initial bursts in these error trials is 52.5 msec (SD = 20.5, minimum = 25 msec). Given the latencies of the long loop reflex, $M_2$, of approximately 35 to 45 msec (Lee & Tatton, 1975; Marsden, Merton & Morton, 1973), it is still possible that error information from the periphery may reach higher centers and return with a corrective command. Table 6 summarizes the percentages and their respective trial frequencies by error category.

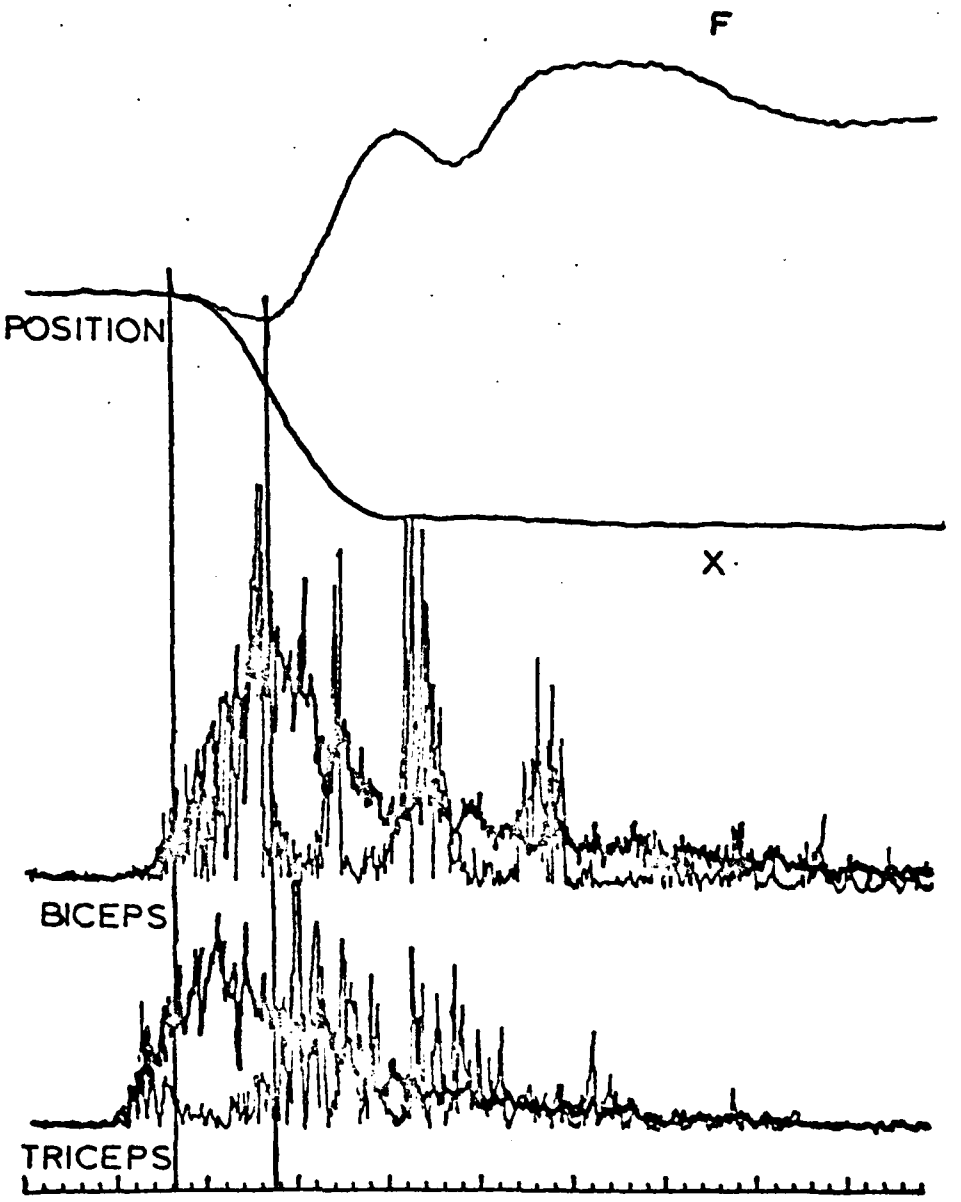



Figure 11. Error trace of subject B.C. Error was toward the simple task toward extension (X). Triceps is agonist for the error and antagonist for the correction. EMGs show a distinct period of antagonist in inhibition in triceps. Each time division is 20 msec.

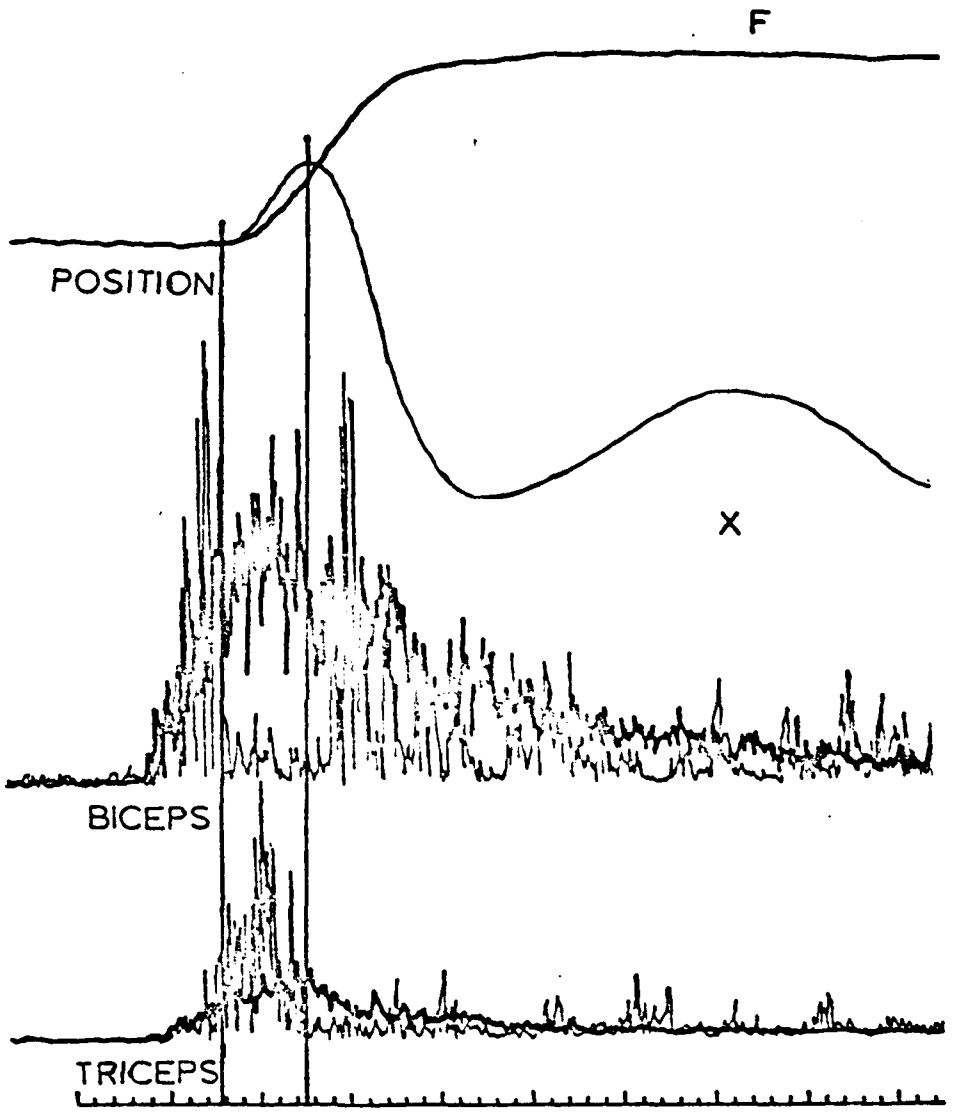



Figure 12. Error trace of subject S.T. Error was toward the simple task toward flexion (F). Biceps is the agonist for the error and antagonist for the correction. EMGs show a distinct period of antagonist inhibition in biceps. Each time division is 20 msec.

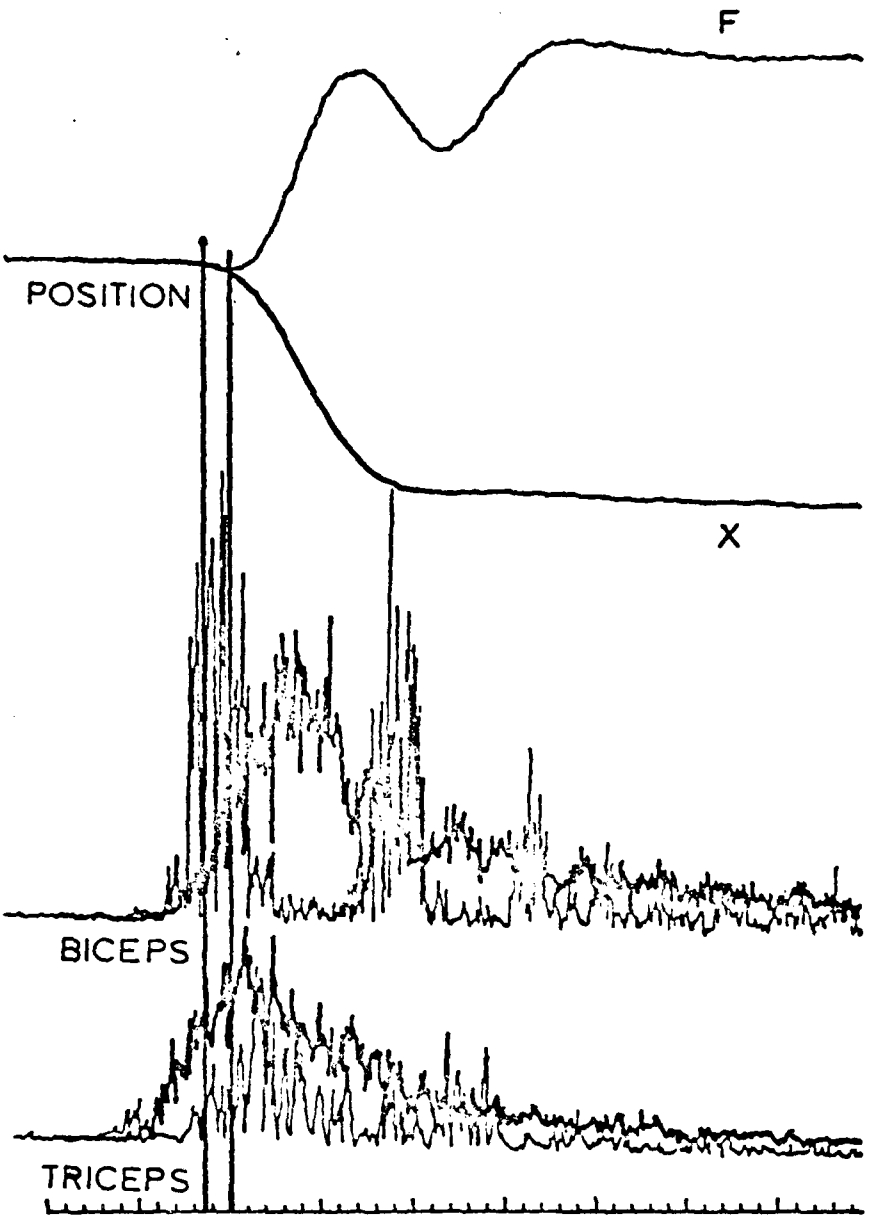



Figure 13. Error trial of subject B.C. showing earliest antagonist inhibition in the triceps approximately 60 msec prior to movement. Triceps is the agonist of the error and antagonist for the correction. Each time division is 20 msec.

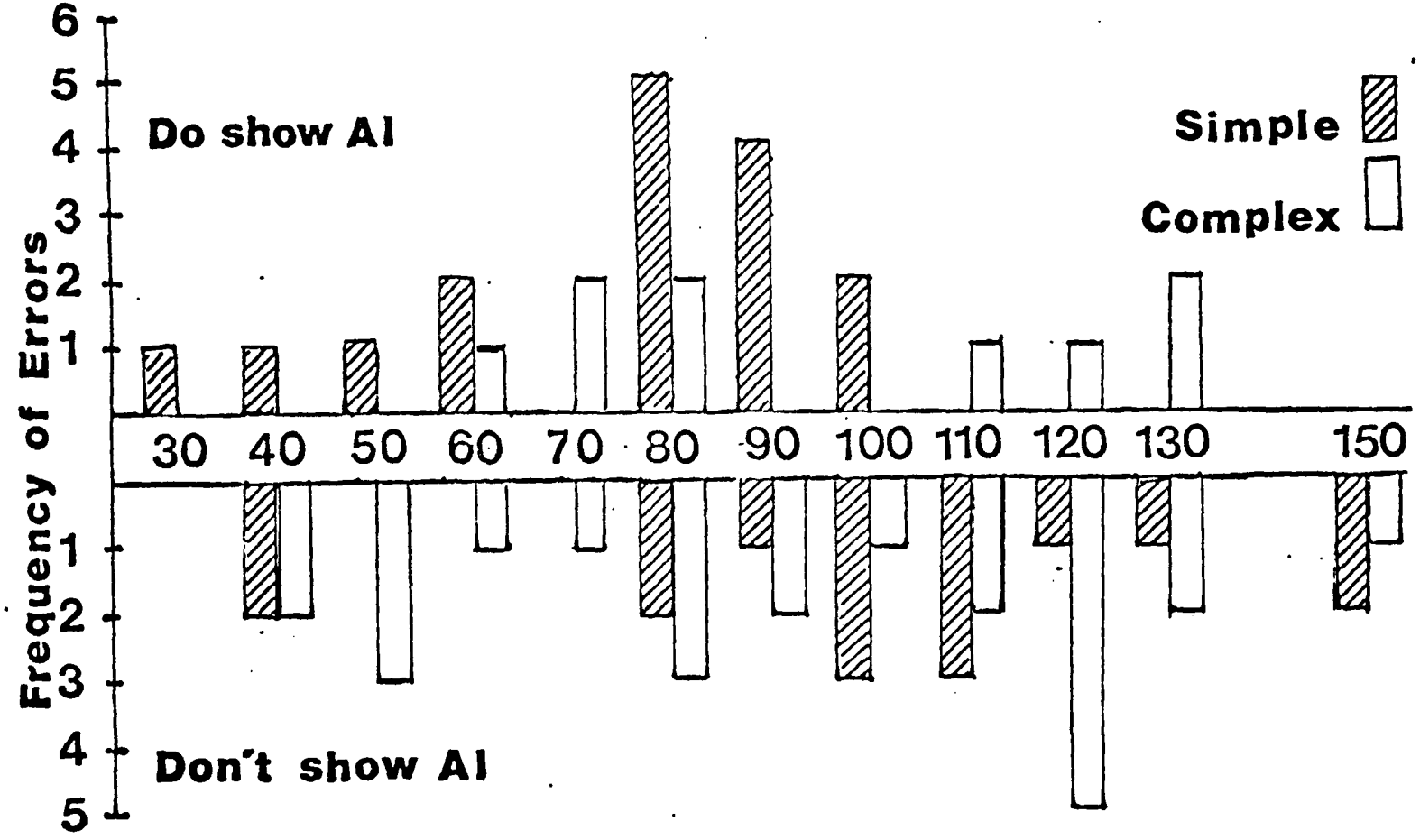



Figure 14. Histogram representing distribution of error correction times in msec in which antagonist inhibition was present (upper portion) and when it was absent (lower portion), and the distribution of errors toward simple (low complexity) and complex (high complexity) responses.

Table 5

Percentages and Trial Frequencies

Error Trials

| | # of Trials | Percent |
|---|---|---|
| Total # of errors | 64 | 100% |
| Errors displaying antagonist inhibition | 26 | 40.6% |
| Errors displaying antagonist inhibition that precedes displacement | 14 | 21.9% |

## Discussion

Experiment 2 examined the effect of task complexity (Hayes & Marteniuk, 1976; Henry & Rogers, 1960; Sternberg et al., 1978) on rapid error corrections. The assumption was made that movement complexity in terms of movement components or segments is reflected in the size and complexity of the efferent command. In terms of a central mechanism that monitors the efferent command, possibly through an internal feedback loop, it was hypothesized that a longer and more complicated efferent command would require longer monitoring time. To test this notion , two movements of differing complexity, an unidirectional movement to a single target and a movement requiring two directional reversals between two targets, were compared in both a simple RT task and a choice RT task.

The simple RT paradigm established that the two tasks required substantially different preparation times, a result that was replicated in the choice condition. Error responses also reflected the complexity difference but in the opposite direction. That is, when a low complexity stimulus was presented and the subject initiated a high complexity movement, the RT resembled the high rather than the low complexity, correct RT. Finally, the ECTs of the high complexity errors did not differ from those of the low complexity errors.

The use of movement reversals to manipulate task complexity

in terms of preparation times was successful (Glencross, 1973; Hayes & Marteniuk, 1978; Henry & Rogers, 1960). High complexity responses RTs were longer than low complexity RTs in both the simple and choice conditions. The lack of an interaction between complexity levels and the simple or choice paradigm indicated that complexity and uncertainty are additive factors influencing different stages of the response preparation process (Massaro, 1975; Sternberg, 1968). The addition of uncertainty to the task required a decision process not necessary in the simple RT task. This additional response selection stage (Theios, 1977) appears to have incremented RTs for the two responses similarly, indicating that the dimension of complexity is independent of this process.

The error responses of the choice condition displayed a reciprocal effect of complexity. Error responses which began toward the high complexity task possessed RTs similar to correct, high complexity responses. To a lesser extent, errors toward the low complexity task possessed RTs similar to the correct, low complexity responses. This finding indicates that on these trials, subjects did prepare the incorrect response. This finding is perhaps the strongest support for the notion that subjects make errors because they anticipate the upcoming stimulus (Schmidt & Gordon, 1977; see also Experiment 1). That anticipation is reflected in a RT that is determined by the nature of the error, not the indicated correct choice. Subjects appear to anticipate

the response choice by preparing one of the two alternatives and executing it when the stimulus comes on, a scenario identical at this point, to that suggested by Schmidt and Gordon (1977). As indicated earlier, anticipation may be responsible for errors occurring, but the cause and corrective mechanism are not necessarily related, as demonstrated in Experiment 1.

The lack of a complexity effect on error correction times did not support the experimental hypothesis. Namely, that the internal monitor would take longer to detect an error in a complex movement command than in a simple one. There are a number of possible situations which could explain this finding, beside the possibility that the central system responsible for rapid corrections simply does not operate in this manner. The assumption that task complexity alters the efferent program may not be valid. Thus the manipulation applied here to create differing degrees of movement complexity may not have created a covariant effect on the efferent command. Internal monitoring then would not reflect this dimension of task complexity. That RTs do reflect this dimension, seems contrary to this explanation. Reaction times have repeatedly been shown to be a linear function of the number of movement elements, in speech (Eriksen, Pollack & Montague, 1970; Klapp, Anderson & Berrian, 1973; Sternberg et al., 1978), in typing (Ostey, 1980, Sternberg et al., 1978), and error movement sequences (Glencross, 1973; Henry & Rogers, 1960). However, the assumption that the

mechanisms responsible for the correction of movement operate in similar ways to those responsible for the preparation of movement also may not be valid. Instead of preparing movement sequences in a serial, additive fashion, the corrective mechanism may process the alternative movement as a "package." If such is the case, responses of different complexity would be corrected in similar time.

One explanation exists which is not contrary to the experimental hypothesis and can explain the data. If the central monitoring proceeds in a serial fashion, and errors occur at the same location in the efferent commands of the alternate responses, then the error correction times would be the same also. In the present experiment, errors occurred as activation of the incorrect agonist, for either type of response. In each type of response the errors were located in the initial portion of the efferent command and consequently required similar latencies for detection. If detection times do not differ, it may be that the initiation of the corrective response may vary with task complexity. However in the responses used here, the corrections were achieved through directional reversals; such reversals would be equivocal relative to the complexity dimension, since each would require similar adjustment of the agonist-antagonist firing ratios (Bizzi, 1980).

EMG analysis of Experiment 2 provided two findings of interest. First, the pattern of EMG activity accompanying error correction appeared to take two forms. About 60% of the error trials displayed patterns of coactivation between the agonist and antagonist. When these trials were compared to the appropriate correct trials, no distinct differences were observed which would unequivocally account for the correction. Corrective agonists did not occur early and increases in agonist activity were not reliably associated with the correction. It is possible that on these trials the error is corrected by a complex interchange of agonist-antagonist activity of the type described by Bizzi (1980). He suggested that movement is achieved through specification of alpha motoneuron activity to both agonist and antagonist muscles.

On 40% of the error trials, the correction was achieved through inhibition of the muscle antagonistic to the correction. Initially, this muscle was active for a brief time (20-90 msec) to generate the error and was then inhibited. With nothing to oppose the corrective agonist, the arm moves in the opposite direction. Similar findings have been reported in finger (Luschei et al., 1967) and limb movements (Hallett et al., 1975a). Hufschmidt and Hufschmidt (1954) required subjects to maintain the biceps in tonic contraction and respond to sensory stimuli by activation of the triceps. However the voluntary contraction of triceps was

preceded by antagonstic inhibition by approximately 50 msec. In a similar task, Luschei et al. (1967) reported antagonist inhibition that preceded the initial agonist burst by 15 msec. Hallett et al. (1975a) also found that the antagonist was suppressed at the beginning of movement prior to inhibition of the stereotypic triphasic pattern. They found that when the antagonist had been kept tonically active, the first sign of response was inhibition of the antagonist from 0 to 50 msec before agonist onset. These findings and others (Capaday & Cooke, 1981) suggest a role in movement regulation more critical than braking or stabilizing for the antagonist. The present experiment indicated a functional use of the rapid inhibition of the antagonist, namely the rapid correction of a movement error.

The second finding of interest is related to onset of the antagonistic inhibition noted earlier. Originally, the intent had been to find evidence of muscle activation responsible for an error correction but preceding the error movement. Instead, there are a substantial number of errors which appear to be corrected via antagonist inhibition. In half the errors demonstrating this pattern, the onset of inhibition precedes the error movement, in some cases, by as much as 40 to 60 msec. This finding eliminates any peripheral information derived from displacement as a possible source of error information. However, an alternative source of error information, still from peripheral

sources could be derived from the initial burst of activity in the muscle generating the incorrect movement. Hulliger et al. (1979) reported the firing of spindle afferents during both steady isometric contraction and during muscle shortening. Therefore, it is possible that spindle activity of the incorrect contracting muscle may have signaled an error. The mean duration of these initial bursts was 52.5 msec, well within the latencies of long loop reflexes through brain stem or cerebral cortex (Lee & Tatton, 1975; Marsden et al., 1973; Cooke & Eastman, 1977) if spindle activity is nearly coincident with EMG onset. Recall that Jaeger et al. (1979) attempted to disrupt spindle information by applying vibration of 100 Hz to both opposing muscles. Although RTs were increased, ECTs did not change. The Jaeger et al. (1979) data suggest that rapid error corrections may still occur when spindle information is disrupted. Their data would not indicate the spindle activity of the initial burst as the source of early error information. It may also be inappropriate to compare reflex latencies to those associated with error detection and correction in a choice response paradigm.

There is additional evidence to suggest that these corrections are centrally generated. When Hallett et al. (1975a) tested a patient with severe pan-sensory neuropathy (deafferentation), they found normal patterns of antagonist inhibition prior to agonist onset. Since the pattern was present in deafferented man,

they concluded that the antagonist inhibition represented a central signal directly to the motoneuron pool. When the same task was performed by cerebellar patients, 12 of 16 patients did not perform normally (Hallett, Shahani & Young, 1975b). Inhibition either appeared too late or not at all, suggesting that the cerebellum plays a role in agonist-antagonist coordination in successive movements. Taken together, these two findings indicate that the pattern of antagonist inhibition is a centrally mediated phenomenon, and in the case of the deafferented patient, not dependent on afferent input from the prior tonic activity of the antagonist.

Although the evidence is not conclusive, the findings reported here appear supportive of internal monitoring of efference and its potential role is rapid error corrections. The complexity dimension tested in Experiment 2 was not successful in altering ECTs, but was interpretable in the framework of central monitoring of efference. Examination of EMG records revealed that in some trials errors were corrected by inhibition of the muscle antagonistic to the reversal, a phenomenon which appears to be centrally mediated (Hallett et al., 1975a). Additionally, this corrective inhibition can occur prior to any movement, ruling out afferent information associated with displacement as the source of the error information. The evidence is not conclusive, since the muscle activity that precedes the inhibition

may also communicate the error information via its spindle afferents. Experiment 2 led to the following conclusions:

1. Movement complexity, as manipulated here, did not alter ECTs, leaving this dimension of efferent monitoring unresolved.
2. A distinct pattern of EMG activity responsible for error corrections was observable on some error trials.
3. There was some evidence that the EMG activity (or lack of it) responsible for the corrective movement preceded the error movement.

## GENERAL DISCUSSION

The initial intent of this study was to extend the existing information base associated with rapid error corrections. More specifically, the investigation focused on the source of the error information and the mechanism by which the rapid corrections were achieved. In choosing between the theoretical explanations of rapid error corrections--internal feedback via a central monitor, false anticipations, or peripheral feedback--the choice resolved into whether the error information was internal to the central nervous system or derived from peripheral sources. If the notion of internal feedback was to be supported, the correctness of the response must be determined from information within the central nervous system. However, if the findings did not rule out peripheral sources then no decision could be made regarding the contribution of internal feedback loops to rapid error corrections.

Experiment 1 attempted a direct test of the source of rapid error corrections. The efference that would have been monitored to correct an error was removed, leaving the only source of error information that present in the afferent information. When efference was removed, rapid error corrections did not occur. However, only when subjects generated their own errors were they capable of detecting and correcting the error rapidly. This

finding is the most significant reported, since it demonstrates that rapid error corrections are dependent not on the afferent input, but on the presence of efference. Experiment 1 also examined the effect of anticipation on both active and passive error responses. In none of the comparisons was anticipation shown to mediate rapid error corrections. It was concluded that although anticipation may be the cause of an error on any one trial, creating experimental expectancies did not explain either the frequency of errors or their rapid correction. The false anticipation hypothesis (Schmidt & Gordon, 1977) was rejected as an explanation of how rapid corrections occur.

Experiment 2 eliminated afferent information associated with displacement as the possible source of error information by demonstrating that in some errors the antagonist inhibition responsible for the correction precedes the error displacement. The possibility that afferent input from spindle activity associated with the initial incorrect muscle burst might signal the error was raised, but deemed unlikely in light of other findings (Hallett et al., 1975a, 1975b; Jaeger et al., 1979). The importance of these results lies in the elimination of one possible source of afferent error information that could generate rapid error corrections. In eliminating this one source, the remaining possible sources of afferent error information are localized "closer" to the central nervous system, leaving fewer alternatives to internal feedback.

The attempt in Experiment 2 to manipulate efferent content via movement complexity did not yield a positive argument. Evidence to suggest that anticipation may be the cause of errors was derived from the similarity of errors RTs to their analogous correct RTs. Finally, one mechanism for the correction of errors was identified from EMG records. Some errors (40%) were corrected through inhibition of the muscle antagonistic to the correction. This pattern of antagonist inhibition prior to agonist activation has been identified elsewhere as the earliest sign of voluntary response in reaction time paradigms (Hufschmidt & Hufschmidt, 1954; Luschei et al., 1967). That it has been identified here as a mechanism responsible for rapid error correction assigns some functional use to the phenomenon.

The results of Experiment 1 and 2 offered qualified support for the existence of internal feedback that monitors efferent commands. The support must be qualified since neither Experiment 1 nor 2 eliminated the previously mentioned source of peripheral error information. What then are the implications for future research, both behavioral and physiological? First, the efferent complexity issue should be reexamined. The assumptions that were left in doubt (e.g. relationship between movement complexity and the efferent command, Hayes & Marteniuk, 1976) should be verified or modified. Alternative movements of very different efferent complexity should be used, not simply movements in opposite directions. Attempts should be made to generate errors at

different points in the efferent command, to determine if the internal monitor is linear as suggested in Experiment 2. Finally, the types of errors that may occur should be varied. In Experiment 2, errors and their corrections were equivalent across the two responses.

Physiologically, it would be desirable to eliminate the spindle afferents associated with the initial EMG burst as sources of error information. Since it is difficult to verify total disruption of spindle afferents from the responding limb via vibration, a pressure cuff nerve block could be used to prevent afferent input. The central monitoring of afference hypothesis would predict no difference with and without nerve block in ability to rapidly correct errors. A similar prediction would hold for deafferented monkeys or humans such as the pan-sensory neuropath tested by Hallett et al. (1975a). If the source of error information is internal than these subjects should be able to execute rapid error corrections similar to normals. However, cerebellar patients may not have this ability if cerebellum is the source of internal feedback as has been suggested (Evarts, 1971; Ito, 1974). Also, these patients do not exhibit the antagonist inhibition pattern (Hallett et al., 1975b) and thus may not be able to execute the rapid correction. Use of these special populations would be accompanied by very specific hypothesis based on the central monitoring of efference and would likely provide

stringent tests of the concept.

The study of rapid error corrections is important and deserving of further investigation for a number of reasons. First, they represent naturally occurring phenomena, a product of the system, not contrived, atypical conditions for the subject. As such, the findings obtained are more easily generalizeable and ecologically valid. Second, they represent an alternative function of internal feedback other than perceptual constancy, adding practicability to the concept. Finally, the study of rapid error corrections may improve the understanding of the organization of movement in the central nervous systems, in both intact and pathological populations. The present findings are encouraging along these lines.

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# Part III

# Spatial Orientation Within Egocentric Space

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## Abstract

Testing the hypothesis that spatial localization can be based on an abstracted spatial location code, rather than on stored proprioceptive information, orientation of an unseen limb was contrasted under same and switched limb movement conditions. In Experiment 1, movements were executed in the midline either vertically upward or horizontally forward in the sagittal plane. These results revealed that same limb accuracy was superior to switched limb accuracy only at the farmost criterion target positions, and it was hypothesized that orientation of a limb could be mediated by the spatial location code if spatial targets remained within the confines of an egocentric reference system. Experiment 2 tested this interpretation more directly by manipulating the availability of body based spatial referents under the same and switched limb conditions. At locations defined a priori as inside egocentric space no differentiation between same and switched limb positioning was found, but as locations defined a priori as outside egocentric space the same limb condition prevailed. It was concluded that spatial referents, in this instance body based, are necessary when the spatial positioning of a limb must rely on the spatial location code.

The increased sophistication of today's technology has brought about considerable changes in the job characteristics of the operator (e.g., pilot, air controllers, etc.) and between the skills of military personnel and the demands which these new technologies make on them. For example, a very high proportion of an operator's immediate surrounding is now likely to be comprised of discrete rather than constant information flow from an instrument panel, radar screen, or computer terminal. Consequently, both the Air Force and the researcher need to maintain cognizance of the often unique characteristics of the operator interfaced with machine in order to ensure maximally efficient performance, decrease mishap likelihoods, and to implement quality system and equipment designs. Thus it becomes more and more important to understand the behavioral characteristics of various discrete movements to spatial locations about the body in order to regulate sophisticated systems.

Perhaps the most desirable performance characteristics of movement to crucial locations, such as on an instrument panel, would be the capability of locating limbs accurately in space using a variety of movement trajectories and that localization be accomplished relatively independent of initial conditions, limb chosen, or the specificity of feedback. Directly relevant to such spatially coordinated behavior is the egocentric referent space for movements about the body and hence the need to investigate the specificity of the proprioceptive system.

Spatial orientation is unquestionably one of the more complex faculties possessed by humans, and as one might expect the orienting process has preoccupied psychologists for many years (Hollingworth, 1909; Holmes, 1919; Riddoch, 1917; Woodworth, 1899). This interest has been especially prominent in the area of motor behavior, where the relationship between orientation and action is an important one. An aspect of this relationship that has attracted considerable attention is the role of the so-called spatial referent system (Lashley, 1951) in the perception and localization of spatial targets (Bernstein, 1967; Gross, Webb & Melzack, 1974; Howard & Templeton, 1966; Luria, 1966; MacNeilage, 1970; Paillard & Brouchon, 1968; Pick, 1970; Russell, 1976; Wallace, 1977).

In this regard, Howard and Templeton (1968) stated that "spatially coordinated behavior is construed as the development and maintenance of a repertoire of response patterns which are moulded and conditioned by the spatial characteristics of the body and of the physical world in such a way that objectives may be rapidly and accurately achieved." (pg. 7). The reference system, then, is proposed as a representation (schema) of physical space that is based on the constructed relationships among spatial referents and to-be-remembered spatial targets (Attneave & Benson, 1968). According to such a view, a spatial target is defined with respect to spatial referents (either body based or environmentally based), and when orientation to a specific target is required the constructed relationship between referent and target is

thought to guide this action.

MacNeilage (1970) was one of the first motor control theorists who stressed not only the importance, but also the necessity of a three-dimensional spatial referent system for movement production. As an alternative to the more traditional views that movement regulation is based on either stored neural commands or stored proprioceptive information from past movements, MacNeilage proposed a control system in which the terminal position of a movement was the critical component for accurate localization. Within this framework, a spatial target is defined within a three-dimensional system and is then transformed into a spatial location code, which is subsequently stored in memory. When localization back to that target is desired, one must determine the current spatial position, retrieve the desired positions "coordinates" from memory, and based on these two pieces of information, generate the motor commands required to execute the intended action.

Although MacNeilage's (1970) original ideas were developed as an explanation of speech production and speech control, they have since been extended to include more overt motor actions of limbs (Russell, 1976). Irrespective of the musculature, however, for the spatial location code and the spatial referent system to be general and viable mechanisms of motor control, it must be shown that 1) the spatial location code can be accessed in memory independent from movements responsible for its initial storage (Russell, 1976) and 2) the presence

(or absence) of spatial referents is a principle determinant of orienting performance.

Wallace (1977) has reported evidence that accurate limb orientation can be accomplished independent of direct proprioceptive inputs. Subjects were required to orient a limb to an experimenter defined spatial target under two conditions; same limb reproduction and switched limb reproduction. In the former condition, a criterion and subsequent reproduction movement were performed with the same limb (e.g. left-left or right-right), thus, stored proprioceptive inputs experienced during the criterion movement were available to guide the reproduction movement. In the latter condition, the criterion and reproduction movements were performed with opposite limbs (e.g. right-left and left-right), and in this instance Wallace argued that it would be difficult for direct proprioceptive inputs gained during the criterion movement to mediate reproduction. Therefore, if accurate reproduction was maintained in the switched limb condition, localization must have been based on some alternate form of information, this being the spatial location code. In an initial experiment, where a criterion spatial target was approached from opposite directions on switched limb trials, Wallace reported that reproduction errors were significantly smaller in the same limb condition. When, however, direction of approach was held constant the superiority of the same limb condition was nullified. Although such results might be viewed

as restrictive in nature, they nevertheless support the basic spirit of the target hypothesis. The first experiment to be presented was meant to further evaluate the utility of the spatial location code by contrasting same and switched limb movements that were executed with vertically upward or horizontally forward in the sagittal plane.[1]

Perhaps a more interesting issue related to the spatial location code is the importance of spatial referents to limb orienting performance. More specifically, if a spatial referent system is important in the orienting process it must be shown that spatial referents influence the accuracy of limb localization. Within the context of an egocentric reference system, which is characterized by spatial referents that are defined entirely with respect to the body schema (Howard & Templeton, 1966), the second experiment attempted to provide corroborative evidence in this regard.

## EXPERIMENT 1

### Method

Subjects. Twelve (N=12) right-handed subjects performed the vertically upward movements and eleven (N=11) right-handed subjects performed the horizontally forward movements. Each participant was recruited from the University of Wisconsin-Madison student population.

Apparatus. In the vertical task, a 2 cm diameter thimble was afixed to a metal rod 90 cm high and 1.3 cm diameter. The thimble could be easily moved along the rod and when released its final

position was maintained by a counter balance weight attached via a pulley system. In the horizontal task, the stylus arm of a Numonics Graphics Digitizer (Model 1224) was constrained to move in one dimension by a 70 cm long and .5 cm wide track. To preclude visual and auditory inputs subjects wore black opaque goggles and headphones.

Procedure. After entering the testing chamber, a subject was seated so that both the midline was directly in front of the movement track and the movement range could be completed by both arms. A familiarization period followed, during which the reproduction conditions and verbal commands were explained. Each trial began with a verbal command that told the subject the limb to be used during the criterion movement. A second command followed and this cued the beginning of the criterion movement. After contacting a mechanical stop, the criterion spatial location was maintained for two seconds, after which subjects returned their arm to the start position area. During the two second location duration each subject was instructed to rehearse the target's spatial position, however, no specific instructions for rehearsal were given. The experimenter returned the thimble or stylus to the original start position, which remained constant throughout the experiment, and then issued the reproduction command for the same or opposite limb. The start position corresponded to a point that intersected the midline and the base of the movement range. Subjects were further instructed to make the reproduction movement

smoothly and directly to the pre-established location, avoiding subsequent adjustments once the movement was terminated.

Design and analysis. On same limb trials the criterion and reproduction movements were executed with the right arm and on switched limb trials the criterion movement was again executed with the right arm, but the reproduction movement was executed with the left arm. For the vertical movements targets were set at 10, 25, 35, 50, and 60 cm from the start position and for the horizontal movements targets were set at 10, 20, 30, 40, and 50 cm from the start position. Due to limitations in horizontal reach it was not possible to maintain identical movement lengths in both instances. A testing session consisted of 30 same limb and 30 switched limb trials, which were further partitioned into six replicates per criterion location. Trials were presented randomly in a way that subjects were given no indication of the reproduction condition prior to the reproduction movement. Localization errors at each target were recorded to the nearest millimeter and inspected for absolute error (AE), constant error (CE), and variable error (VE). For the results within each movement plane the data analysis consisted of five planned, orthogonal comparisons (t ratios) between the same and switched limb movements at each of the five criterion targets. If direct proprioceptive information is necessary for accurate localization, these comparisons will be significant, however, if the spatial location code can effectively

guide localization these comparisons will be non-significant.

Results and Discussion

Vertically upward movements. The AE analysis revealed that two of the five comparisons were significant (see Table 1): At the 50 and 60 cm targets same limb reproduction was more accurate, $t(48) = 2.59$ and 5.24, $p < .05$. For CE three of the five comparisons were significant: At the 25 cm target switched limb reproduction was more accurate, $t(48) = 2.80$, $p < .05$ and at the 50 and 60 cm targets same limb reproduction was more accurate, $t(48) = 5.27$ and 3.08, $p < .05$. In VE one comparison reached significance and this was the 60 cm target where same limb reproduction was more accurate, $t(48) = 5.37$, $p < .05$.

INSERT TABLE 1

Horizontally forward movements. For AE significant comparisons were found at the 40 and 50 cm targets, $t(44) = 3.99$ and 4.46, $p < .05$. In both instances, same limb reproduction was better than switched limb reproduction. CE revealed that four comparisons were significant: At the 20 cm target switched limb errors were smaller than same limb errors, $t(44) = 2.89$, $p < .05$ and at the 40 and 50 cm targets same limb errors were smaller than switched limb errors, $t(44) = 4.51$ and 5.33, $p < .05$. The comparison at the 30 cm target was also significant, however, it is difficult to assess its meaningfulness because the positive magnitude of same limb errors is nearly equivalent to the negative magnitude of switched limb errors. In fact,

INSERT TABLE 2

if the analysis were to be done on the unsigned means the difference would be non-significant. Finally, for VE significant differences were found at the 40 and 50 cm targets and these revealed that same limb reproduction prevailed, $t(44) = 2.38$ and 2.53, $p < .05$.

At the outset it was thought that same limb performance would either prevail over or be equivalent to switched limb performance. The data obviously failed to substantiate such an expectation. Instead, the primary feature of the data indicates a consistent superiority of the same limb condition at the two farmost targets, whereas, equivalence between the two conditions is maintained at the remaining criterion targets. Furthermore, this pattern is clearly seen for movements vertically upward in the sagittal plane and horizontally forward in the sagittal plane. Although other comparisons were significant they certainly were not as prevalent, especially when all three error measures are considered. These data, just like Wallace's results, appear to place some restrictions on the generality of control by the spatial location code and at this point it seems reasonable to speculate on the conditions of these restrictions.

Perhaps the role of body reference points is more important than has been previously recognized. More specifically, spatial targets where same and switched limb reproduction is equivalent can be said to be within an individual's egocentric reference system. As such, body reference points are available during the orienting process and the

additional information supplied by these referents establishes a spatial location code robust enough to be used effectively by either limb. In contrast, the spatial targets where same limb reproduction is more accurate can be said to be outside the egocentric reference system, in which case the necessary information afforded by the body reference points is lacking. Although reproduction in the same limb condition can still benefit from proprioceptive inputs gained from the criterion movement, reproduction in the switched limb condition is forced to rely on a less than optimal spatial location code. Consequently, localization accuracy can not be maintained at the level of the same limb condition. Such an interpretation is strengthened by the fact that the 50 or 60 cm targets in the vertically upward direction were above the head; a position where additional body reference points would be unavailable.

Rather than invoking the preferred explanation of egocentric space and body reference points, however, these findings could be viewed as a movement length effect. That is, the closer targets and shortest movement lengths were always inside egocentric space, whereas, the farthest targets and longest movement lengths were always outside egocentric space. To rule out the movement length explanation another experiment was conducted in which same and switched limb movements were performed vertically downward in the sagittal plane. Such a manipulation meant that the shortest movement lengths were now outside

the reference system and the longest movement lengths were now inside the reference system. Movement lengths identical to those in the vertically upward task were used and fifteen subjects were tested. The egocentric referent hypothesis predicts that same-switched limb differences will occur for the shorter movement lengths, but no differentiation will occur for the longer movement lengths. In contrast, the movement length hypothesis predicts same-switched limb differences for the 50 and 60 cm movements. Unfortunately the results failed to entirely support either position: Same and switched limb accuracy were equivalent at all spatial targets. Although this experiment did not support the egocentric referent hypothesis outright, they nevertheless rule out movement length as the sole description of the previous findings.

## EXPERIMENT 2

The foregoing interpretation certainly raises questions about the relationship between spatial referents and the spatial location code during orientation of an unseen limb. The purpose of this second experiment was to determine whether body based spatial referents have a direct mediating effect on reproduction errors when localization must be based on the spatial location code. The switched limb procedure was again used, but now spatial targets in two-dimensional space were selected on an a priori basis to represent locations either inside or outside the egocentric reference system. If body referents

are necessary for accurate limb localization when direct proprioceptive cues are not available, the expected pattern of results is rather straightforward: at locations defined as inside egocentric space same and switched limb accuracy should be equivalent, whereas, at locations defined as outside egocentric space accuracy in the same limb condition should prevail.

Method

Subjects. Twelve (N=12) right-handed participants were recruited from the University of Wisconsin-Madison.

Apparatus. To allow movements in two-dimensions a Numonics graphics digitizer (Model 1224) was used. The digitizer was mounted on a formica plate (44 x 82 x 1.3 cm), which in turn rested on a table 67 cm in height, such that movements were executed horizontally forward in the sagittal plane. The recording head was placed 60 cm from the base of the movement range so that a stylus arm could be easily moved to any position on the formica plate. By the very nature of the movement task, criterion movements had to be restricted to one-dimension, and this was accomplished by requiring subjects to move inside a .5 wide and 55 cm long track, which was subsequently removed for the reproduction movement. The digitizer was interfaced with a Digital Corporation PDPe computer which recorded the X-Y coordinates of the terminal position on a reproduction movement. To preclude visual sources of information subjects wore black opaque goggles.

INSERT FIGURE 1

Procedure. The general procedures and instructions were identical to those stated previously. Three criterion targets were selected to represent locations within egocentric space (see Figure 1): Target 2 corresponded to a point 20 cm in front of the midline and was chosen as it represented a location where same and switched limb accuracy were equivalent in the previous experiment. Targets 1 and 3 corresponded to locations 15 cm to the left and right of the midline and 20 cm from the base of the apparatus at a straight line distance of 26 cm from the start position. These were considered inside the reference system because they were approximately in line with the shoulders and could be coded in conjunction with the body reference point. In addition, three targets were designated as outside the reference system. Target 4 was placed 40 cm in front of the midline and it was the point at which same and switched limb performance first became differentiated in the previous experiment. Targets 5 and 6 were placed 35 cm to the left and right of the midline, at a straight line distance of 41 cm from the start position. The latter two locations were defined as outside the reference system because they were nearly 20 cm beyond each shoulder, and it would be difficult to code these points in conjunction with some body referents.

Design and analysis. One modification in the experimental design

was the addition of the left-left and left-right limb combinations. The experimental design, then, corresponded to a completely within subjects 12 x 4 x 6 (subjects x limb combination x location) factorial. The data analysis consisted of twelve planned, orthogonal contrasts (t ratios) which were based on the predictions stated earlier. At each criterion target the localization accuracy between the right-right and the left-right combinations was compared and the localization accuracy between the left-left and right-left combinations was compared. Note that here we chose to have the limb of the reproduction movement constant, rather than the limb of the criterion movement as in Experiment 1. Technically it should make no difference to the target hypothesis which of the movements remains invariant, however, from a procedural point of view it is probably more prudent to keep the reproduction movement the same so as to circumvent potential differences resulting from anatomical or mechanical considerations; especially in instances where the midline was crossed. Subjects performed a total of 72 trials that were partitioned into three replicates per limb combination at each of the six criterion targets. Trials were once again randomly presented and the primary dependent measure was radial error, which was defined as the absolute deviation of the reproduction terminal location from the criterion target.

Results and Discussion

Analysis of the data at the spatial targets defined as inside egocentric space revealed that only one contrast was significant: right-right localization errors were smaller than left-right localization errors at spatial target 1, $t(165) = 2.09$, $p < .05$ (see Table 3). The pattern of results was markedly different at the locations defined as outside egocentric space. At criterion targets 4, 5, and 6 right-right accuracy was better than left-right accuracy, $t(165) = 3.22$, 4.17, 2.37, $p < .05$, and similarly, left-left accuracy was better than right-left accuracy, $t(165) = 3.48$, 2.00, 3.25, $p < .05$.

Of primary interest in Experiment 2 was the effect of body reference points on switched limb reproduction accuracy, relative to the same condition. It was reasoned that if spatial referents are essential when limb orientation is based on the spatial location code, inside egocentric space the switched limb condition would be as accurate as the same limb condition, but outside egocentric space, where body referents were eliminated (or at least made difficult to use), switched limb errors would be larger than same limb errors. The fact that localization accuracy between the same and switched limb conditions is equivalent only at spatial targets inside egocentric space provides clear support for such a position. Moreover, the results at targets 2 and 4 provide both a partial replication of Experiment 1 and argue against the idea that the previous findings

were more a function of the reproduction limb being different.

## General Discussion

Employing the switched limb technique (Wallace, 1977), the present experiments were designed to investigate the conditions under which the spatial location code (MacNeilage, 1970) could direct the accurate spatial positioning of an unseen limb. Experiment 1 revealed that subjects were able to effectively use the spatial location code, but only when criterion targets were within certain movement ranges. It was subsequently argued that these ranges defined the boundaries of an egocentric reference system, and it appeared as if body based spatial referents were responsible for these findings. Experiment 2 further examined this proposed relationship between body reference points and the utilization of the spatial location code by directly manipulating the availability of the spatial referents. These results showed that accurate spatial positioning was achieved by the spatial location code only if body referents were available, thus, supporting the idea that the ability of the location code to guide orienting performance is dependent upon information gained from spatial referents. Consequently, for limb movements within the present context the generality of MacNeilage's (1970) target hypothesis seems to be restricted to spatial positions within egocentric space.

These findings are also related to a growing number of studies

concerned with the underlying neural mechanisms responsible for control of spatial localization. Fel'dman (1974 a,b) believes that the position a limb achieves is dependent on the length-tension relationships among the agonist and antagonist muscles involved in the movement. Fel'dman likened this process to the operation of a spring. Operationally, irrespective of how a spring is stretched, when the forces acting on the spring are released it always assumes an established equilibrium point. Within the framework of spatial positioning, the specified terminal location of the limb can be viewed as the equilibrium point. Not only is this concept appealing, but its explanatory power is confirmed by neurophysiological evidence concerning alpha-gamma coactivation (McCloskey, 1980; Vallbo 1974 a,b), as well as positioning studies with monkeys (Bizzi, 1980; Bizzi, Dev, Morasso, & Polit, 1978; Bizzi, Polit, & Morasso, 1976) and humans (Cooke, 1979, 1980; Kelso, 1977).

This length-tension hypothesis can certainly be incorporated into the present scheme. In fact, these experiments add another dimension to this type of control. It appears that when a two-dimensional spatial target is well coded, via body referents, the motor control system can parameterize the length-tension properties of either limb equally well, even though the relationship among agonist and antagonist muscles may be different for the criterion and reproduction movements (e.g. as in switched limb movements to locations 1 and 3). Without

the spatial referents the settings in the contralateral limb can not be accomplished effectively because the spatial location code is too inexact.

These results also point out that more specificity is needed when referring to the spatial schema or referent system. Typically, distinctions between types of reference systems have been disregarded. For example, one is unable to discern whether Russell (1976) refers to an egocentric or exocentric reference system (see Howard & Templeton for their differences) in his elaboration of MacNeilage's target hypothesis. Such a distinction is not a trivial one. Benton (1969) reviews a number of studies concerning spatial disorders suggesting that the type of disorder is dependent upon the type of reference system disrupted. Howard and Templeton (1969) also make a clear distinction between the two reference systems. We are not advocating complete functional independence because both undoubtedly influence the orienting act. Rather, since so little is known about each system's operational characteristics, it may be more advantageous to initially examine them independently.

This discussion would be incomplete without briefly considering one possible challenge to the present interpretations. Rather than invoking the concept of an egocentric reference system with its body referents, the data may be the result of distortions in the alignment of body position, which is an artifact solely at the distant targets.

As a function of trying to reach the farther target positions, the limb nears full extension and causes a corresponding rotation of the upper body. In the same limb condition the rotation during the criterion and reproduction movements is always in the same direction, however, in the switched limb condition the rotation is in opposite directions. Therefore, in this latter instance the rotation could create misperceptions of the criterion target, and in turn adversely effect localization accuracy. The closer targets would not induce this rotation so neither same nor switched limb movements would be affected. Perhaps the most straightforward test of this alternative would be to restrict movements to inside the egocentric reference system and then in some way disrupt perception of the body referents. If our account of the data is correct, switched limb accuracy should be worse than same limb accuracy. In any event, until this or similar experiments are conducted, we are compelled to maintain the functional significance that has been associated with the spatial referent system concept and believe it merits continued examination.

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TABLE 1

Reproduction Accuracy (cm) of the Same and Switched Limb Conditions at each Criterion Spatial Target for the Vertically Upward Movements

| Limb | | Locations | | | | |
|---|---|---|---|---|---|---|
| | | 10 | 25 | 35 | 50 | 60 |
| Same | AE | 2.10 | 2.62 | 3.38 | 2.53 | 1.85 |
| | CE | 1.93 | 2.10 | 2.13 | 0.65 | 0.20 |
| | VE | 1.50 | 2.62 | 2.95 | 2.58 | 1.69 |
| Switched | AE | 2.54 | 2.53 | 3.49 | 3.49 | 3.79 |
| | CE | 2.18 | 0.69 | 1.82 | -2.00 | -1.35 |
| | VE | 1.60 | 2.24 | 3.21 | 2.60 | 3.51 |

TABLE 2

Reproduction Accuracy (cm) of the Same and Switched Limb conditions at each Criterion Spatial Target for the Horizontally Forward Movements

| Limb | | Locations | | | | |
|---|---|---|---|---|---|---|
| | | 10 | 20 | 30 | 40 | 50 |
| Same | AE | 2.81 | 3.98 | 2.73 | 1.89 | 1.65 |
| | CE | 2.25 | 3.71 | 1.15 | -0.65 | -0.44 |
| | VE | 1.28 | 1.83 | 2.21 | 1.74 | 1.51 |
| Switched | AE | 3.52 | 2.98 | 2.43 | 4.01 | 4.02 |
| | CE | 3.29 | 2.15 | -0.70 | -3.08 | -3.31 |
| | VE | 1.76 | 2.04 | 2.05 | 2.54 | 2.36 |

TABLE 3

Mean Radial Error (cm) of the Four Limb Combinations

at each Spatial Target

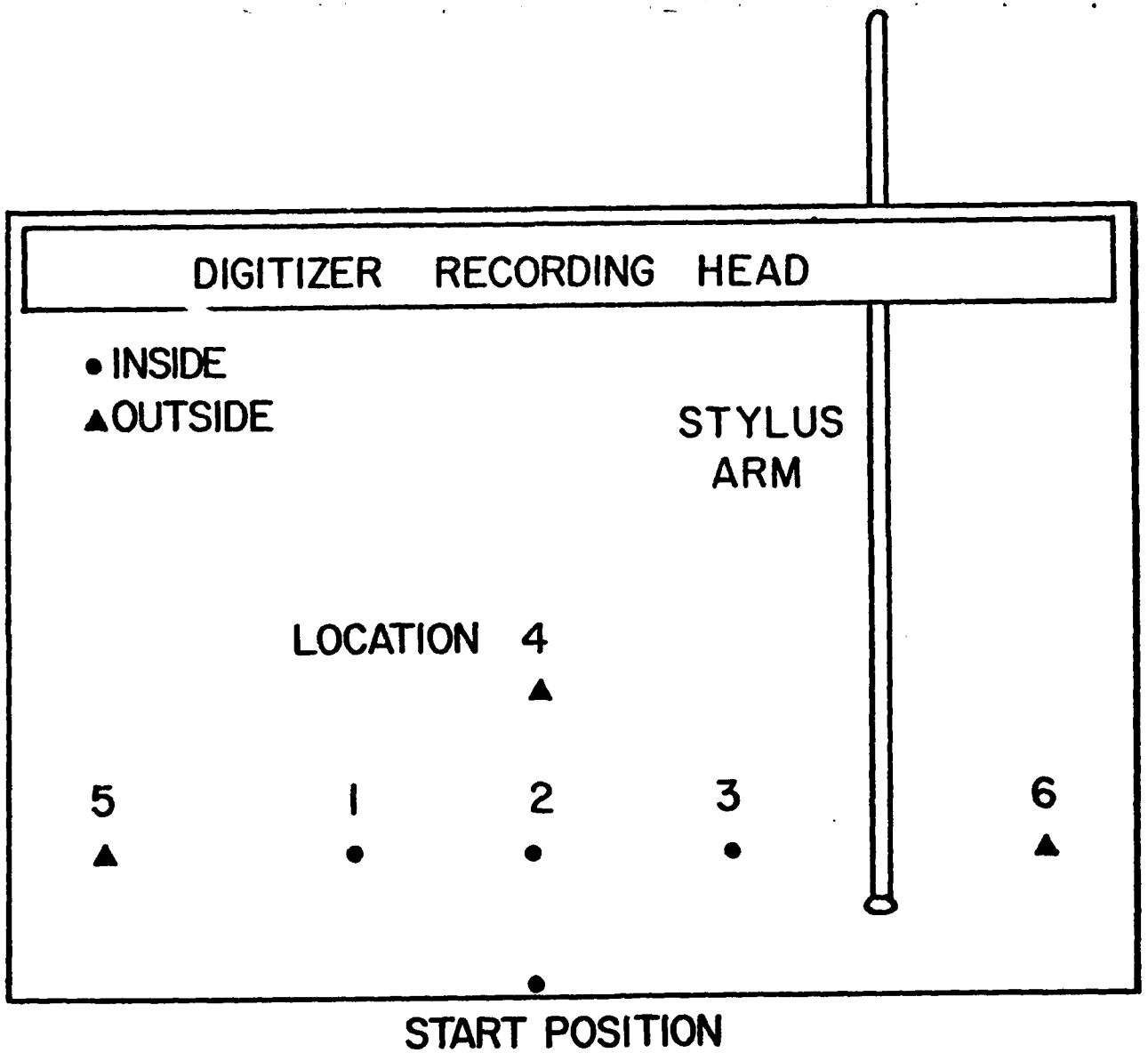
| | Limb | | | |
|---|---|---|---|---|
| Location | RR | LL | RL | LR |
| 1 | 4.10 | 5.18 | 5.70 | 5.63 |
| 2 | 4.22 | 4.64 | 5.24 | 4.60 |
| 3 | 4.77 | 5.37 | 5.31 | 5.02 |
| 4 | 3.25 | 3.57 | 6.12 | 5.61 |
| 5 | 4.70 | 4.77 | 6.24 | 7.76 |
| 6 | 4.62 | 3.76 | 6.14 | 6.36 |

## Figure Caption

Figure 1. Graphic of the apparatus and criterion spatial targets.

AD-A118 575 WISCONSIN UNIV-MADISON MOTOR BEHAVIOR LAB F/G 5/10
CODING, ORGANIZATION AND FEEDBACK VARIABLES IN MOTOR SKILLS.(U)
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UNCLASSIFIED 10 AFOSR-TR-82-0620 NL




DIGITIZER RECORDING HEAD
• INSIDE
▲OUTSIDE
STYLUS ARM
LOCATION 4
5
1
2
3
6
START POSITION

# Error Detection and Correction with Organized Movement Sequences

George E. Stelmach
Les D. Szendrovits

## Abstract

Error detection and error correction experiments were conducted to examine the assumption that organizational processes play an important role in motor learning and control. During the initial phase of each experiment the sensory aspects of five movements were held constant while the organizational structure (sequential vs random) of the movement sequences was varied. In the learning phase of both experiments the effect of organization produced increased reproduction accuracy for the structured movement sequences compared to those that were random. This benefit of organization carried over into the error detection and correction parts of the experiments where it was shown that improved error detection and correction capabilities were assisted by the manner in which the movements were presented. The importance of cognitive processes is discussed in terms of past and contemporary accounts of motor learning and control.

# Error Detection and Correction with Organized Movement Sequences

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Fundamental to the learning and performance of all skills is the capability to recognize and correct errors. While feedback and practice have been shown to enhance this capability the practicality of highly repetitive training is unrealistic and costly. Compounding the problem is the increasing complexity and sophistication of the equipment which trainees are required to master. One way in which to alleviate some of the demands of training and skill proficiency may be through organizational strategies. Such strategies represent a cognitive viewpoint emphasizing a more vigorous interaction between learner and environment whereby the trainee can develop an efficient strategy to store and retrieve movement information. The consequences of organized over simply repetitive training would be faster acquisition, higher levels of proficiency, increased learning capacity, the ability to transfer skills to novel situations and an enhanced ability to detect and correct movement errors. Therefore, it is crucial for viable implementation to understand the role and application such strategies play in learning and memory. More specifically if it can be demonstrated that such strategies improve the ability to detect and correct errors the implications are clear: trainees

would be better able to recognize and correct their own errors and improve performance releasing the instructor from valuable retraining time constraints.

Traditionally theories of motor control and memory have been preoccupied with the sensory aspects of movement, claiming that variables such as feedback and practice were the primary determinants for the development of accurate performance (Adams, 1971; Adams & Goetz, 1973). Of course, these variables are not the only ones that may affect movement reproduction. Certainly there are a variety of information sources which contribute to learning and performance. The main thrust of past efforts has been directed at understanding the characteristics of information derived from proprioception. This thrust has lead to the creation of a number of theoretical constructs that regard sensory information as the primary basis upon which movement reproduction depends (Keele & Ells, 1972; Kelso, 1977, Laabs, 1973; Marteniuk, 1973). Recently these thoughts have been revised, assigning a greater importance to cognitive processing (Diewert & Stelmach, 1978; Gentile & Nacson, 1976; Marteniuk, 1976; Pew, 1974; Schmidt, 1975). The basic postulate is that individuals actively plan, organize, and abstract information that culminates in effective strategies for movement control.

This perspective has generated contemporary research in which cognitive strategies have evolved in a variety of forms: verbally labelling movement endpoints (Shea, 1977), advance planning of a

terminal location prior to movement (Roy & Diewert, 1975; Kelso & Wallace, 1978), formulating images of locations (Szendrovits & Glenberg, Note 1), formation of spatial referents for locations (Stelmach & Larish, 1980), and organization of information in terms of contextual rules for movement reproduction (Stelmach & Diggles, Note 2). Such strategies have been shown to enhance movement reproduction accuracy compared to a no strategy or inappropriate strategy condition by supplementing efferent or afferent information (Kelso & Stelmach, 1976). The actual implementation of a particular strategy by subjects is generally ensured through instruction, by structuring the task in a way that the appropriate strategy is easily discerned, or through both instruction and task structure. The mechanism by which this improved performance is attained can be explained via the formation of abstract codes which provide additional nonkinesthetic information regarding the target and its context which in turn assist and guide the movement closer to the desired location. The source or locus of this effect has been hypothesized to be in any one of three stages of information processing-encoding, storage, or retrieval.

One of the more fruitful approaches toward assessing the effects of cognitive strategies for movement information has been through the organization paradigm (Diewert & Stelmach, 1978, Gentile & Nacson, 1976; Nacson, Jaeger & Gentile, 1972). In this paradigm one group of subjects practice with a sequentially ordered set of movements

(usually equidistant from each other) and another group practices with randomly ordered movements while attending to the relationships among endpoints. The findings have consistently demonstrated that through movement presentation order subjects are able to enhance reproduction accuracy. The basic assumption being that subjects actively seek to determine and use the structure and order presented in the task and that information which is identified and stored in an orderly manner results in greater movement accuracy and less forgetting. The consistent order together with contextual relationships among movement endpoints are believed to facilitate the transformation of information to a spatial map and subsequent retrieval. A method by which this could be accomplished is through the formation of a cognitive strategy which specifies a rule describing the endpoints of the movements. The implications are that memory representation and retrieval are enhanced by organizational processes resulting in more accurate movement reproduction (Stelmach & Diggles, Note 2).

It appears from the preceding discussion that cognitive processes can and do contribute toward reproduction performance accuracy. One important contribution toward accurate performance may be the ability to detect and correct errors. In the past feedback and practice variables have been shown to enhance this capability by increasing the strength of an internal reference mechanism against which

errors are compared (Adams & Goetz, 1973). Since memory representation and retrieval are further enhanced by organizational processes one would predict increased discriminability between target locations and also error correction capabilities beyond sensory consequences. The following experiments reason that if organization is a potent variable in motor behavior it should be able to supplement the sensory aspects of movement and provide greater accuracy in the detection and correction of errors. In addition, this potency would be further realized if it could be shown that organization is generalizable to recognition processes. As a result two experiments involving error detection and error correction were conducted to test the logic outlined above using a linear positioning task.

## Experiment 1

### Method

Subjects. A total of 40 right-handed volunteers randomly assigned to two groups participated in the experiment. All of the participants were students at the University of Wisconsin between the ages of 19 and 26.

Apparatus. The apparatus consisted of a linear positioning slide. A handle mounted on an aluminum plate and connected to a ball bearing sleeve runs along three steel rods (115 cm long x 2 cm diameter) which are attached at the ends to a steel platform (120 cm long x 40 cm wide x 25 cm high). Two rods mounted horizontal and

parallel to each other are positioned 20 cm above the base of the platform. The third rod is also situated horizontally but sits 10 cm above the base. The handle is grasped by the subject and displaced in a right-to-left direction from a fixed starting position. A pointer attached to the handle assembly on the experimenter's side of the apparatus moves along a metric scale (in millimeters) in order that the subject's criterion and reproduction movements can be recorded. An adjustable stop peg aligned by the experimenter defined movement lengths.

Procedure. The experiment was composed of two phases, a learning phase and a test (error detection) phase. The procedures employed in the learning phase were typical of those associated with a linear positioning task in which blindfolded subjects wearing headphones moved the handle of the apparatus to a physical stop followed by a reproduction attempt. In the learning phase the experimenter provided knowledge of results to the nearest half centimeter. Two independent groups of subjects, Sequential and Random learned a series of five movements. The presentation of the five movements together with their reproduction represented one trial block. The sequential group learned the movements in a constant order, 10-20-30-40-50 cm, for ten trial blocks. The random group received the same five movements but in a random order which varied for each of the ten trial

blocks. Both groups were administered identical verbal instructions.

Following the learning phase (50 trials) both groups entered the error detection phase which consisted of a two choice recognition task. Subjects were forced to discriminate between previously learned locations (targets) and new locations by moving to a physical stop and responding "old" to learned positions and "new" to all others. The "new" target positions were located either ±5%, ±10%, or ±15% from the learned target locations. For example, ±10% of the 30 cm target is ±3 cm; therefore a 27 or 33 cm location constituted the 10% difference limen for this target. The limens for the other positions were determined similarly. In order to keep these "new" locations from overlapping the previous learned targets only three of the original five locations, 10-30-50 cm, were employed for the error detection phase and subjects were instructed accordingly. Each subject performed two blocks of 36 trials with a single block consisting of 18 targets and 18 new movements. Consequently, an equal number of "old" and "new" movements were presented in a randomized order within a block of 36 trials. Knowledge of results was not provided for this phase of the experiment.

Absolute error and constant error were employed as dependent variables in the learning phase. The data were examined by analysis of variance with Organization, Movements, and Trial Blocks as factors; the last two factors are within-subject variables. For the error

detection phase, percent correct was the dependent variable. Separate analyses of variance were performed on the targets and limens with Organization, Targets, and Trial Blocks as factors; the last two factors are within-subject variables. The analysis of the limens in the error detection phase was identical to that of the targets with Organization, Limens, and Trial Blocks as factors where Limens and Trial Blocks are within-subject variables.

Results and Discussion

For absolute error, the results of the learning phase supported the notion of improved performance for the organized movement sequences. Organization $F(1,38) = 4.11$, $p < .05$, movements, $F(4,152) = 3.20$, $p < .05$, and trial blocks, $F(8,342) = 3.41$, $p < .01$, main effects were significant. The effect of organization demonstrated the superior reproduction accuracy of the sequential group, mean of 1.65 cm, compared to the random group, mean of 1.82 cm, during the learning phase. The trials effect indicated that, with practice, both groups were able to reduce their errors from trial block 1, mean of 1.96 cm, to trial block 10, mean of 1.47 cm. Figure 1 displays the performance of the two groups throughout the learning trials. During early trials both groups exhibited similar performance, whereas in later trials, the sequential group manifested less error and began to show the advantage of organization over the random group. The main effect of movements indicated that the 10 cm location was reproduced most

accurately among the five movements. In summary, the sequential group given identical feedback and practice conditions as the random group but provided with a structured sequence of movements resulted in superior performance.

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Insert Figure 1 about here

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The results of the analysis of constant error for the learning phase revealed that the effect of movements, $F(4,152) = 7.90$, $p < .01$, and the organization x movement x trial block interaction, $F(36,1368) = 2.64$, $p < .01$, were significant. However, other than to show that the shortest movement was overshot while longer movements were undershot, this analysis did not convey much meaningful information because it was characterized by extremely low scores. For example, the effect of trials showed errors of -.58 cm and -.37 cm for the first two blocks, respectively. It is difficult to imagine how subjects could consistently improve on such low scores. Considering these low constant error scores throughout the trials the results of this analysis are uninterpretable except in terms of response biasing.

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Insert Table 1 about here

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The results of the error detection phase for limens produced a

significant main effect of limens, $F(2,76) = 47.84$, $p < .01$. Scheffe's post hoc analysis revealed that all three limens differed from each other, $p < .01$, with the 15% limen having a mean of 72.3% correct, the 10% and 5% limens having means of 55.7% and 43.7% correct, respectively. The analysis on the targets produced a significant main effect of organization, $F(1,38) = 6.41$, $p < .05$. This effect was manifested in the ability of the sequential group to recognize the targets, mean of 70.1% correct, better than their counterparts, mean of 59.3% correct. Table I shows this effect clearly. In summary, the results of the error detection phase demonstrated that organization does increase the discriminability between the targets and limens as reflected in the ability of the sequential group to recognize the targets correctly. To further substantiate this ability to discriminate between targets and limens an index of sensitivity, d', was calculated for both the sequential and random groups. The advantage of the d' index is that it takes into account both the hit and false alarm rates and is completely independent of the decision rule that subjects may use. The value of d' obtained for the sequential group was .348 while d' for the random group was .156. Since the d' value was much larger for the sequential group, one can argue that through organization subjects are, in fact, better able to discriminate the targets from the limens.

This finding supports the contention that cognitive processes supplement the sensory aspects of movement, and further, extends the generalizability of organization to a recognition paradigm.

## Experiment 2

Just as important in the acquisition and retention of movements as error detection is the ability to correct errors once they have been identified. The prediction for the second experiment was identical to the previous one. If the sequential group was able to employ a more efficient strategy through organization than the random group, performance would be reflected in smaller errors following correction.

### Method

Subjects. Thirty, task-naive, right-handed volunteers from the University of Wisconsin between the ages of 19 and 30 participated in the experiment, and were randomly assigned to two groups.

Apparatus. The same linear positioning slide was used as in Experiment 1.

Procedure. The procedures were exactly the same as in Experiment 1 with the exception that the recognition task was replaced by an error correction task following the ten blocks of learning trials. In the error correction phase subjects moved to a stop positioned at either ±5%, ±10%, or ±15% of the length of the criterion movements practiced in the learning phase. Once again only three, 10-30-50 cm,

of the original five locations were tested to eliminate overlapping of limens and locations. Subjects were instructed accordingly. Following the movement to a stop, the experimenter gripped the sleeve of the slide to prevent slippage during the removal of the stop. After the stop had been removed subjects attempted to correct the error by moving either forward or backward to the nearest learned location. Each subject in the error correction phase performed three blocks of 18 trials (3 replicates of the 6 limens for each target) with randomization of locations occurring for an equal number of limens in each block.

Absolute and constant error were the dependent variables for both phases of the experiment. The learning phase and the error correction phase were analyzed separately using analysis of variance. The three factors in the learning phase were Organization, Movements, and Trial Blocks with the last two factors being within-subject variables. In the error correction phase the following factors were examined: Organization, Trial Blocks, Movements, Limens, and Type of Correction (forward or backward), the last four factors being within-subject variables.

Results and Discussion

The results of the learning phase for absolute error produced significant main effects of organization, $F(1,28) = 17.13$, $p < .01$,

movements, $F(4,112) = 3.84$, $p < .01$, and trial blocks, $F(9,252) = 5.08$, $p < .01$. It was evident that the sequential group with a mean of 1.57 cm reproduced the locations with greater accuracy than the random group, mean of 2.06 cm. The effect of movements indicated that the 10 cm location was performed with the greatest accuracy. Throughout the learning trials both groups displayed consistent decreases in error from trial block 1, mean of 2.10 cm, through trial block 10, mean of 1.47 cm. The performance of the sequential and random groups during the learning trials mirrored that depicted in Figure 1. These results together with those of Experiment 1 add further confirmation to the efficiency of cognitive processes in the learning of movements. The results of the analysis of constant error for the learning phase revealed significant effects of movements, $F(4,112) = 3.43$, $p < .01$, trial blocks, $F(9,252) = 3.68$, $p < .01$, and an organization x movement x trial block interaction, $F(36,1008) = 1.42$, $p < .05$. Unfortunately, these results were again characterized by extremely low scores, as in the error detection experiment, and do not provide meaningful interpretations except for range effects; short movements were overshot while longer ones were undershot.

In this study, primary interest was in the error correction task. The assumptions outlined earlier were confirmed through the analysis of absolute error. Illustration of this confirmation is reflected in the performance of the two groups shown in Figure 2. The sequential

group with a mean of 2.19 cm was able to correct their errors significantly better, $F(1,28) = 12.85$, $p < .01$, than the random group that had a mean of 3.47 cm. A significant movement x limen interaction, $F(4,112) = 2.99$, $p < .05$, also appeared. Scheffe's post hoc test revealed that the difference between the 15% and 10% limens and the 15% and 5% limens on the 50 cm target was significantly different from all other pairs of means at the other locations. Since there were no significant effects of limens nor an organization x limen interaction it was suspected that the increased error was a function of the rather large correction that subjects had to perform. That is, there was a greater potential for error for a 15% correction to the 50 cm target compared to other limens and targets.

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Insert Figure 2 about here

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The analysis of constant error produced four significant effects: type of correction, $F(1,28) = 85.07$, $p < .01$, movement x type of correction, $F(2,56) = 16.56$, $p < .01$, limen x type of correction, $F(2,56) = 12.59$, $p < .01$, and movement x limen x type of correction, $F(4,112) = 6.12$, $p < .01$. Type of correction showed that when subjects were placed short (to the right) of the targets and asked to make a forward correction, their responses ended short (mean of -.61 cm) following the correction. Similarly, when a backward correction was necessary the correction finished short or to the left of the

target giving a positive score (mean of 1.27 cm). In the movement x limen x type of correction, corrections became progressively less accurate as the size of the movements and limens increased, a result consonant with the findings of the absolute error data.

In summary, the results of the error correction phase revealed that the performance of the sequential and random groups differed radically. The sequential group, provided with a structured sequence of movements, was able to correct their errors more efficiently.

## General Discussion

Traditional theories of motor behavior have advocated that memory representation is dependent almost entirely on the sensory aspects of movement e.g., feedback and practice (Adams, 1971; Adams and Goetz, 1973; Laabs, 1973). In this paper it was posited that cognitive processes, in the form of organization, represent potent variables for the learning and performance of movements and both experiments clearly demonstrated this view.

In the learning phase the sequential groups were provided with a structured movement sequence while the random groups received unstructured sequences. Under identical conditions of practice, knowledge of results, and sensory feedback the sequential groups displayed markedly superior performance during the learning trials as compared to the random groups, results which are consonant with

previous work (Nacson, Jaeger, & Gentile, 1972; Nacson, 1973; Diewert & Stelmach, 1978). It was suggested earlier that organizational processes may operate through the formation of a cognitive rule that develops as a consequence of the interrelationship between contextual relations among movement endpoints and presentation order. In other words the structure that is presented enables subjects to form rules that can specify spatial referents for movement reproduction. For unstructured sequences contextual relations may not be perceived, or more likely, are not as easily discernable when embedded in random presentations. Since some information may not be discernable to the subjects, the appropriate rule for reproduction cannot be developed either at all or to the same extent as in the case of structured movements.

For the test phase it was predicted that the sequential groups which had already displayed better performance through organization during learning trials would be able to retain this advantage in the absence of knowledge of results for the detection and correction of errors. For the error detection task two main points must be emphasized. First, organization does increase the sensitivity of the subjects to recognize correct responses. Second, the effects of organization can be extended to recognition tasks, arguing for the importance and generalizability of cognitive processes. Similarly, the results of the error correction task revealed that the ability to correct errors

was enhanced through organization. This effect, illustrated in Figure 3, was quite prominent where the performance of the sequential and random groups after correction is plotted as a function of the distance before correction.

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Insert Figure 3 about here

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While the error correction experiment certainly reinforces the importance of organization it also addresses the issue of where the effects of organization occur, encoding or retrieval. Subjects, when asked to make a correction from different limens, are in fact reproducing the targets from novel starting positions. This represent a manipulation of starting location, distance, and direction. In other words, the context at the time of endocing differs with respect to all movement parameters from the context at the time of reproduction i.e., retrieval. If the locus of organization is relegated to the encoding stage, then one would predict that a manipulation of context would negate the effects of organization since the information necessary for reproduction does not match the information at encoding. Conversely, if the effects of organization are attributed to a retrieval rule that aids the selection of critical items from memory, context manipulation should be less damaging to reproduction accuracy and organizational processes should maintain

accurate performance. In spite of contextual differences, the sequential group was more accurate in reproducing the practiced locations. Thus, the effects of organization appear to be strongly linked with retrieval processes rather than encoding; and accurate movement reproduction as a result of organization seems to depend on the retrieval process (Stelmach & Diggles, Note 2).

It has been demonstrated that the organization of movement information improves movement accuracy to a target and error detection and correction capabilities. The notion that simply ordering information results in such improvements goes beyond explanations of movement accuracy in terms of sensory feedback and repetition. Indeed, it is equally tenable in light of current popular conceptualizations of movement reproduction such as the mass spring analogy which models agonist-antagonist muscle combinations whose length-tension characteristics determine final accuracy (Bizzi, 1980; Feldman, 1966a, 1966b; Polit & Bizzi, 1979). While this account may be insightful in explaining how limb movements are controlled, it is however, unable to explain the differential performance of the two groups without involving a framework that incorporates cognitive variables. In summary, the overall results of these studies support the contention that organizational or cognitive processes improve reproduction accuracy beyond the sensory aspects of movement and directly relate such processes to motor learning and control.

The implications of the findings of the experiments in this report demonstrate benefits for trainees, instructors, and ultimately the Air Force. The findings hold promise for assuring success for trainees during training and once they have left training and are on their own. For instructors the implications are that attention to principles of organization may negate the need for constant error correction later in practice. These benefits can accumulate both temporal and monetary savings. Furthermore, the fact that organizational processes can be generalized to a recognition task further demonstrates its practicality, importance, and a need for additional development.

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Footnote

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Table 1

Mean percent correct recognition on the three targets

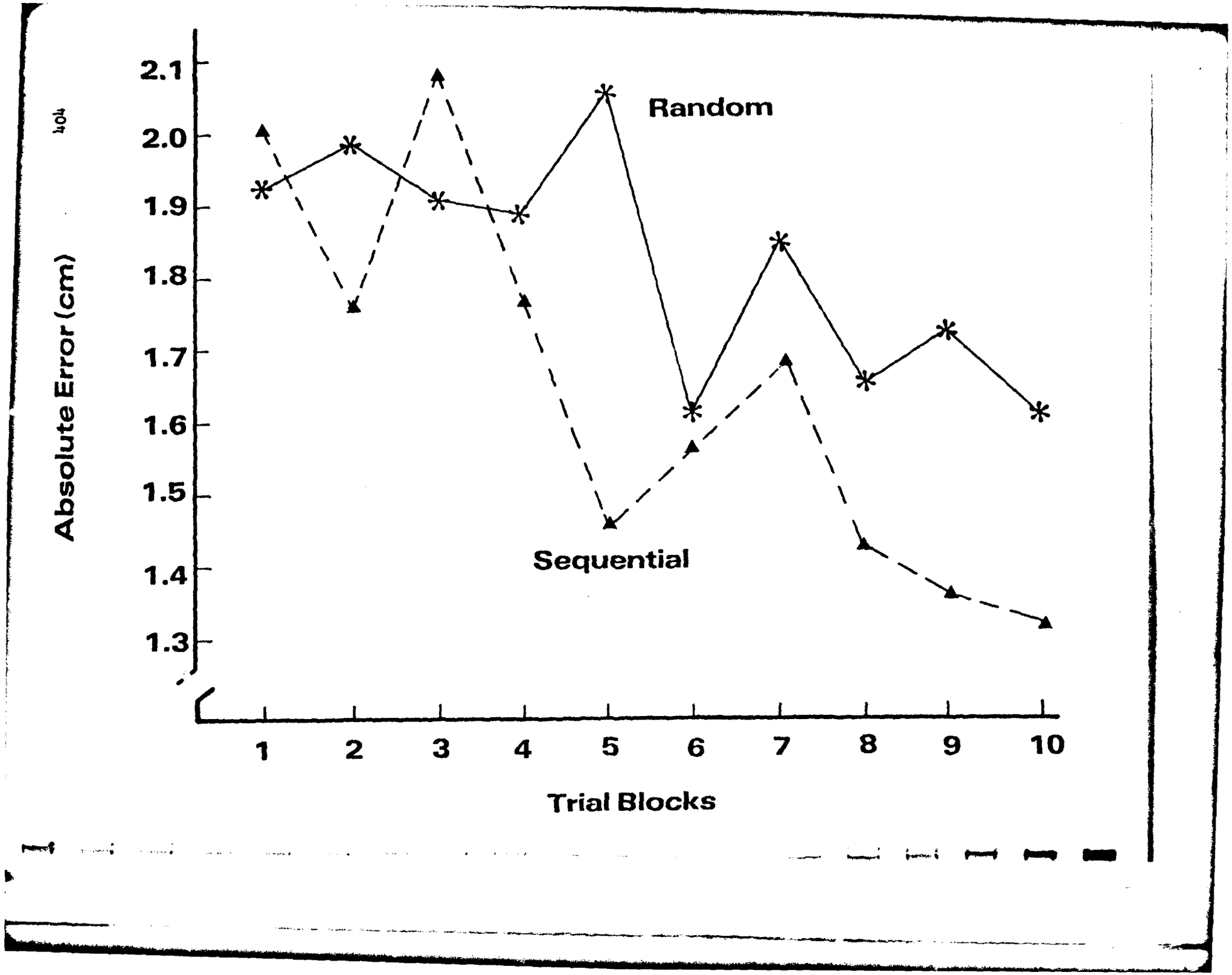
| | Targets (CM) | | | |
|---|---|---|---|---|
| Groups | 10 | 30 | 50 | Mean |
| Sequential | 68.8 | 71.2 | 70.3 | 70.1 |
| Random | 59.6 | 64.2 | 54.1 | 59.3 |

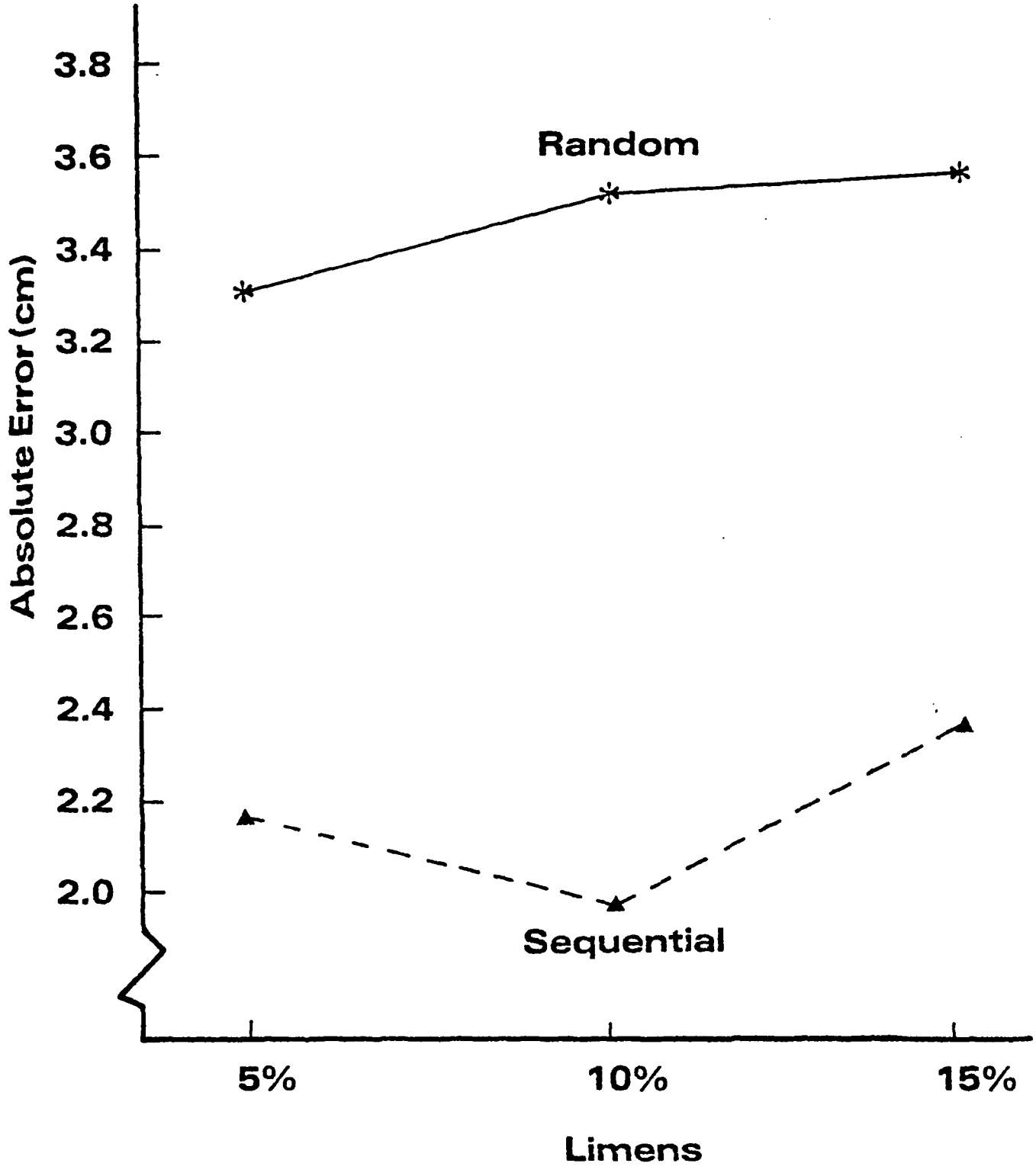
## Figure Caption

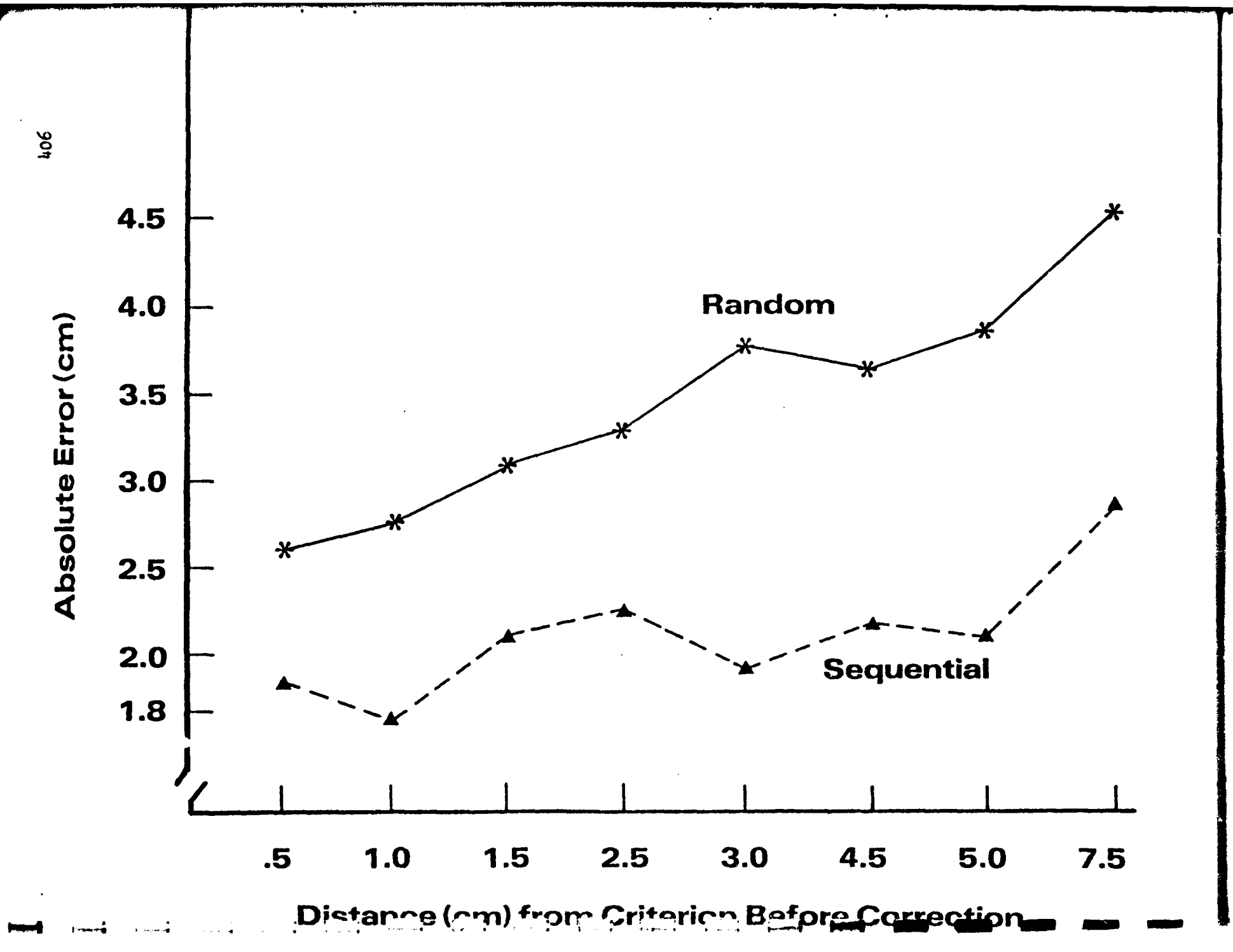
Figure 1. Mean reproduction errors of the sequential and random groups plotted as a function of absolute error and trial blocks during the learning phase.

Figure 2. Mean reproduction scores of the sequential and random groups after correction as a function of absolute error and limens for the error correction phase.

Figure 3. Mean reproduction scores of the sequential and random groups after correction as a function of absolute error and distance before correction for the error correction phase of Experiment 2. (There are only 8 distances represented on the abscissa instead of 9 because the 15% limen at the 10 cm location (1.5 cm distance) and the 5% limen at the 30 cm location (1.5 cm distance) were averaged as one score for each group for the 1.5 cm distance).


Absolute Error (cm)
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
Random
Sequential
1
2
3
4
5
6
7
8
9
10
Trial Blocks


3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
Absolute Error (cm)
Random
Sequential
5%
10%
15%
Limens


Absolute Error (cm)
4.5
4.0
3.5
3.0
2.5
2.0
1.8
Random
Sequential
.5
1.0
1.5
2.5
3.0
4.5
5.0
7.5
Distance (cm) from Criterion Before Correction

# Movement Organization:

# The Locus of its Benefits

George E. Stelmach
Virginia A. Diggles

## Abstract

Two experiments on movement organization were performed using a linear positioning task to examine the locus of organization benefits. Organization was imposed by presenting five equidistant targets sequentially as opposed to an unorganized random presentation. The results of Experiment 1 revealed that organization was beneficial to performance, but specific to the performance phase in which it was presented and not transferable to other phases. Experiment 2 crossed random and sequential groups with a switched limb/direction procedure to separate encoding and retrieval processes. There was no benefit of organization where limb-specific consequences were available or when direction and distance cues were reliable; however, organization did benefit retrieval processes when encoding cues were unavailable. Little evidence was found to implicate encoding or storage process as the locus of organizational benefits, while most of the findings suggest retrieval processes as the locus.

# Movement Organization: The Locus of its Benefits

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Contemporary research stresses the mechanisms which determine how individuals acquire and process information. Where before motor behaviorists searched primarily for the empirical relations governing acquisition, transfer and forgetting, recent efforts seek to discover how the mind works in registering, storing and utilizing information present in a dynamic environment. Intimately tied to these processes is the phenomenon of movement organization, the locus of whose benefits is the subject of this report. By pinpointing the locus of organizational benefits, techniques for improving application of this phenomenon may be developed, advancing the understanding of the cognitive aspects of skilled performance which may be manipulated for improvement in physical training. The findings obtained here have implications for the efficient instruction and training of physical and combative skills to military personnel. Specifically, the successful application of the reported benefits of movement organization should shorten initial training time to acquire a motor skill, this benefit increasing as the complexity of the skill increases. Additional anticipated advantages include the attainment of higher levels of task proficiency in a given period of time and greater success when the organizational strategies are applied to tasks in a novel context.

Approximately ten years ago, memory for movement information was characterized as a collection of "traces" whose strength developed as a function of practice and feedback (Adams, 1971; Laabs, 1973; Pepper & Herman, 1970; Stelmach, 1974). More recently, there has been a change in how movement information in memory is viewed, ascribing more responsibility to the cognitive and volitional aspects of movement and the performer, respectively (Kelso & Wallace, 1978; Roy & Diewert, 1975; Shea, 1977). The effects of organization, used here to refer to the orderly nature either inherent in the incoming information or derived by the individual, have been documented in memory research in both verbal (see Puff, 1979; and Tulving & Donaldson, 1973 for review) and motor areas (Gentile & Nacson, 1977; Diewert & Stelmach, 1978). The notion that the arranging of information according to some orderly principle should facilitate memory processes is in opposition to the "trace" view of memory and in accordance with the active, cognitive view mentioned above.

The benefits of organization have been demonstrated in positioning tasks (Nacson, Jaeger & Gentile, 1972; Nacson, 1973; Diewert & Stelmach, 1978), however the locus of these benefits is not well established. Adopting the conventional framework of three major memory processes - encoding, storage, and retrieval (Crowder, 1976; Klatzky, 1975) - one can pinpoint a number of loci where the presence of organization would

likely result in differential predictions. In encoding, the initial registry of incoming information (perception) and its subsequent translation into an abstract form present two possibilities; while an increase in retention capabilities through a more resilient storage code offers a third. Experimentally, the processes of encoding (Gentile & Nacson, 1977) and storage (Diewert & Stelmach, 1978) have each been indicated as the locus of the phenomenon, the rationale being that the benefits attributed to these earlier memory processes are reflected in retrieval processes in an additive way. However, retrieval processes, which include memory search and response generation, provide additional alternatives which warrant consideration. The inclusion of response generation in retrieval processes reflects the importance of planning and cognitive involvement to final accuracy in addition to the error detection and correction components usually thought responsible for terminal accuracy in slow movements. Where this planning component is emphasized in slow movements, such as the preselection paradigm (Stelmach, 1977), it may provide an additional source of control for accuracy and thus should not be dismissed from research employing slow movements.

The first efforts at investigating the effects of organization on memory for movement were those of Nacson et al. (1972) and later Nacson (1973). Reasoning that the encoding of movement information

is a generative process by which input is transformed, ordered, and altered to preserve the essential characteristics in a limited capacity storage, Nacson, et al. (1972) contended that the purpose of practice was to develop appropriate rules for encoding information. Gentile and Nacson (1977) suggested that in positioning tasks, input consists of the contextual relationship among the positions to be learned, rather than the individual feedback characteristics of each position. In testing this notion Nacson et al. (1972) sought to demonstrate that accuracy in positioning could be facilitated by emphasizing the spatial relationship among the movement categories through verbal instructions to half the subjects. As expected, those with instructions performed with greater accuracy. Later, Nacson (1973) examined the effect of constant versus varying orders of presentation. Constant orders of presentation and recall all resulted in smaller error than the varying order, and within the constant presentations a sequential order was superior to other orders. The conclusion drawn from these results indicated that each target position was encoded in relation to the others, a process facilitated by the constant order of presentation. In general, the interpretation of these results place the locus of organization's benefit in the encoding stage (Gentile & Nacson, 1977).

More recently, Diewert and Stelmach (1978) attempted to expand the Nacson findings in a series of experiments using experimenter-presented organization of five equidistant targets on a linear slide.

In this context, a sequential order of presentation constituted organization of movement information. Unorganized presentations were achieved through varying random orders. A summary of their findings revealed that: (a) for experimenter-presented organization to be effective in reducing error, the subject must be aware of or attending to the organizational principle, achieved in this instance through instructions; (b) when subjects learn under either sequential or random orders and are switched to the alternate order later in practice, accuracy in the subsequent trials is characteristic of performance in the learning phase, that is, the sequential group that switched to a random order maintained lower errors characteristic of their sequential performance, indicative of a beneficial transfer; (c) when organized orders of presentation are used in a free recall paradigm, groups provided with knowledge of results perform about the same as those without knowledge of results; (d) when subjects were allowed to freely recall the target positions, subjects chose a sequential order regardless of the order of presentation and performed with greater accuracy than groups receiving experimenter-presented organization. On the basis of these findings, Diewert and Stelmach (1978) concluded that the benefits of organization lie in a superior memory representation, suggesting a dynamic interplay between feedback and higher order strategies in memory processes.

The present research effort sought to test predictions dependent upon organizational benefits residing in particular loci. A number of

variables were manipulated to probe memory processes for an indication of the process or processes most benefitted by movement organization. Experiment 1 examined the generalizability of organization and its interaction with knowledge of results and varying retention intervals. Experiment 2 examined the effect of organization where contextual information is made unreliable for movement reproduction.

## Experiment 1

Though the previous research efforts indicated a particular aspect of memory to be facilitated by organization, it remained to be seen whether this benefit was resistant to time and forgetting. The first of the experiments presented here tested the retention characteristics associated with organization as well as replicating some of the Diewert and Stelmach findings. More specifically the purpose of Experiment 1 was four-fold: (1) to seek further support for the beneficial nature of organization to motor learning and retention; (2) to test the notion that organization may enhance retention over time; (3) to examine the interaction of organization and knowledge of results; and (4) to further examine the generalizability of organization learning to random, unorganized conditions.

### Method

Subjects. Subjects were graduate and undergraduate students at the University of Wisconsin-Madison and were randomly assigned to one of four experimental groups (N = 30). Both male and female subjects were included and were evenly distributed across groups. All subjects were right-handed and one was paid for his or her services.

Apparatus. The apparatus consisted of a linear positioning slide. A handle mounted on an aluminum plate and connected to a ball bearing sleeve traversed three steel rods (115 cm long x 2 cm diameter) which attached at the ends to a steel platform (120 cm long x 40 cm wide x 25 cm high). Two rods mounted horizontal and parallel to each other were positioned 20 cm above the base of the platform. The third rod was also situated horizontally but sat 10 cm above the base The handle was grasped by the subject and displaced in a right-to-left (left-to-right was possible also) direction from a fixed starting position. A pointer attached to the plate supporting the subject's handle on the experimenter's side indicated error on a metric scale (in millimeters) to record the subject's criterion and reproduction movements. An adjustable stop aligned by the experimenter defined movement lengths.

Procedure. Prior to the testing the subject was comfortably seated with the body's midline directly in front of the middle target. The subjects were familiarized with the apparatus and given instructions on performance of the task. The subjects wore blindfolds and ear phones to minimize the noise associated with the slide. The general procedure required the subject to grasp the handle of the slide at its starting position and move the slide at a slow, uniform pace until it encountered the experimenter-positioned stop, defined as the criterion location. After 2 seconds, the subject was instructed to

release the handle and the experimenter repositioned the slide at the starting position. The subject was then asked to reproduce the criterion location as accurately as possible. For those groups receiving knowledge of results, error in terms of millimeters, short or long was provided. In addition to the instructions regarding the experimental procedure, all subjects were given instructions designed to direct their attention to the physical location of the targets and their interrelationships.

Design. Testing was divided into two phases, a learning phase and a retention phase. Each phase consisted of ten trial blocks, with each block including one trial at each of the criterion locations (10, 20, 30, 40 and 50 cm). In Phase I, half the subjects received a sequential presentation of the five equidistant targets from shortest to longest while the other half received random permutations of the five targets, orders varying from block to block. Half the subjects in each of these groups received knowledge of results during the learning phase. During the retention phase, no knowledge of results were given. The retention interval between the learning phase and retention phase varied from immediate (0 days), to 2 days, to 4 days with one third of the subjects testing under each interval. During the retention phase, half the subjects who learned under a sequential order switched to a random order, while a similar switch was made by

half the subjects who had learned under a random order. In Phase I, subjects were nested within the Organization x knowledge of results x trial blocks x movement distance design with repeated measures on the last two items. In Phase II the retention interval factor was added to the analysis. Analyses of variance were applied to the absolute and constant error (AE and CE) from each phase.

Results and Discussion. In Phase I, all main effects were significant in AE, $p < .05$. The sequential group performed with less error than the random group, $F$ (1,116) = 4.64. Subjects who learned with knowledge of results had less error than those who learned without knowledge of results, $F$ (1,116) = 11.04. The trial effect was caused by error descreasing with an increasing number of trials, $F$ (9,1044) = 7.84. The movement distance effect was caused by error increasing as the length of the movement increased, $F$ (4,464) = 4.99. In Phase II, only the main effect of organization and movement Distances were significant at $p < .05$, $F$ (3,96) = 5.46 and $F$ (4,384) = 2.64, respectively.

Tukey's post hoc analysis revealed that in Phase II, the groups performing under a sequential order during the retention phase were doing so with less error than the groups performing under a random order, regardless of the order under which they learned. Figure 1 illustrates the benefits of a sequential presentation both in the learning phase (Phase I) and the retention phase (Phase II). Organization

does not appear to affect the rate of learning as a significant organization x trial block interaction would have indicated

Insert Figure 1 About Here

in Phase I. Note that in Phase II the groups performing under a sequential order do so with less error than those performing under a random order. This finding only partially replicated the Diewert and Stelmach findings.

During Phase II, the determining factor for the groups with mixed orders of presentation was the order they were currently performing under and not the order under which they learned. The encoding specificity principle maintains that the specific encoding operations performed on an item at the initial storage determine the retrieval conditions which will facilitate the most accurate access to the memory trace (Tulving & Thomson, 1973). Although both the Diewert and Stelmach (1978) data and the present finding argue against any encoding specificity, they do not support the same interpretation of the facilitating effect of organization to memory. That encoding specificity does not exist suggests that the phenomenon of organization has little effect on encoding processes per se. The results presented indicate that organization is a potent variable only at the time of reproduction and does not appear to transfer to other contexts. If such is the case, the locus of any benefits of organiza-

tion would be localized in either an enhancement of some short term storage or in retrieval processes. The lack of a significant organization x retention interval interaction would seem to argue a similar case. One would expect that a stronger memory representation achieved by an organized presentation would display greater benefits after longer retention intervals relative to a random presentation.

Further evidence that organization is not intimately related to the encoding and storage processes is derived from the additive nature of its interaction with knowledge of results. Knowledge of results has been traditionally considered a critical factor in encoding and storage of movement information (Adams, 1971, 1976; Newell, 1977). Table 1, however, illustrates that organization can be an equally powerful factor in performance. In Phase I, the random group with knowledge of results performed at about the same error level as the sequential group without knowledge of results. About the same benefit was achieved with both knowledge of results and organization present as the deficit seen when neither is present. The additive nature of these variables suggests that they are exerting effects on different processes.

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Insert Table 1 About Here

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The results from the analysis of the CE data were not very

informative, as the benefits of organization were not distinguishable in CE. In Phase I, the main effects of trial blocks, $F(9,1044) = 10.53$, and movement distance, $F(4,464) = 15.33$ were significant at $p < .05$ along with the organization x movement distance, $F(4,464) = 3.69$, the trial blocks x movement distance, $F(36,4176) = 2.48$, and the organization x trial blocks x movement distance, $F(36,4176) = 1.98$, interactions. In Phase II, only the movement distance main effect, $F(4,384) = 2.77$ and trial blocks x movement distance, $F(36,3456) = 1.66$, interaction were significant at $p < .05$. The lack of any significant organization effects in CE is puzzling. One would likely intuit that an error reflecting directional biases would be sensitive to any manipulation that enhances the contextual information associated with the stimuli. Nevertheless, movement organization had no differential effect on the magnitude of over- and under-shooting. One explanation for the lack of an organization effect may be derived from the observation that in the CE data, errors were quite small, ranging from -1.0 to .4 cm (AE scores seemed small also). With such small errors to begin with, even the benefits of organization could not further reduce error, resulting in an apparent floor effect in CE.

## Experiment 2

The results of Experiment 1 cast some doubt on whether

organizational benefits heighten the representation of movement information. Experiment 2 manipulated certain variables of the physical display to make them unreliable after subjects had learned the five target locations. More specifically the second experiment probed the extent to which location information is dependent on the limb-specific sensory consequences of movement or the physical context in which they occur. One method of separating these two aspects of movement reproduction is the switched-limb technique originally developed by Wallace (1977) to test MacNeilage's target hypothesis (1970) and Russell's (1976) application of it to limb movement. This theoretical position holds that kinesthetic information about location is converted into an abstract location code which specifies a location in terms of the individual's spatial coordinate system. This system develops with experience as the relationship between various body parts and personal space. The transformation of specific kinesthetic information from limb position to an abstract location code renders the information independent of the movements associated with its encoding and yet leaves sufficient information to generate reproduction commands to the location (Russell, 1976). Thus it appears that this technique presents one method of separating the encoding of information from its retrieval. The switched-limb procedure does not prevent the storage of kinesthetic endpoint information, however, it does prevent the direct use of this

information during reproduction attempts (Wallace, 1977). Conditions are compared wherein the limb used for the criterion movement to the experimenter-defined target and the limb used for the reproduction movement may be either the same (e.g. right arm-right arm) or different (e.g. right arm-left arm). Also, the direction from which the reproducing limb approaches the target may be switched, either from the same direction as the criterion movement or from the opposite direction. Wallace (1977) found that when the direction of movement reproduction was held constant, switched-limb reproduction was equal to same-limb reproduction. However, when both limb and direction were opposite to those used in the criterion movement, deficits occurred. Wallace (1977) reasoned that if the location code were a relationship between the location of the limb and the surrounding context, then switching the direction of reproduction altered the context sufficiently to make that relationship unreliable. The deficit due to this directional manipulation appeared only when limb-specific kinesthetic information was also unreliable. If this rationale reflects the true situation then organization of that context may facilitate performance when both limb and direction are switched.

To test this notion and gain better insight into the locus of organizational benefits, the switched-limb paradigm was combined with organizational techniques. It was hypothesized that organization

would attenuate the deficit previously seen (Wallace, 1977) when the relationship between the individual, the targets, and the physical context is made unreliable.

Method

Subjects. Subjects were 48 graduate and undergraduate students at the University of Wisconsin-Madison and were randomly assigned to one of six experimental groups. Both male and female subjects were included and were evenly distributed across groups. All subjects were right-handed and task-naive.

Apparatus. The apparatus used in Experiment 1 was also used in Experiment 2.

Procedure. Experiment 2 consisted of two phases of testing. Phase I was a learning phase in which the general procedures were identical to the learning phase of Experiment 1. That is, subjects received 10 trial blocks, each block consisting of one replicate at each target. For half the subjects the order of the targets within a block was sequential, while the other half received random orders of the target presentation. All subjects received exact knowledge of results in the learning phase. During the rest interval between phases, instructions for Phase II, the test phase, were administered for implementation of the switched-limb manipulations. One third of the subjects continued using the same limb-same direction (Sa-Sa) procedure used by all in the learning phase. One third of the subjects

received the criterion movement with the right arm and were required to reproduce the target with the left arm from the same starting position, thus using the same direction as the criterion (Sw-Sa).[1] The remaining third of the subjects received the criterion as before, but were required to reproduce the target with the left arm from the opposite direction of the criterion and its starting position (Sw-Sw). In this phase, those subjects who learned under a sequential order continued under a sequential order as was similarly the case with those learning under a random order. The test phase consisted of six trial blocks in which no knowledge of results were given.

Design. The same criterion locations used in Experiment 1 were used in Experiment 2. In Phase I, subjects were nested within the organization factor to yield an organization x trial blocks x movement distance design with repeated measures on the last two items. In Phase II, subjects were nested within the organization and switched limb/direction group combinations to yield an organization x groups x trial blocks x movement distances design with repeated measures on the last two factors. Analyses of variance were performed on AE and CE scores for each phase.

Results and Discussion. Table 2 contains the mean data from the terminal performance of the random and sequential groups in Phase I and their subsequent performance under the switched-limb manipulation in Phase II. As in Experiment 1, distances and

trial blocks in Phase I of Experiment 2, were all significant at $p < .025$ for AE scores, $F(1,42) = 11.48$, $F(4,168) = 3.71$, and $F(9,378) = 6.47$, respectively. In AE scores of Phase II, the main effects of groups (defined by the switched-limb manipulation) and trial blocks were significant, $F(2,42) = 13.25$ and $F(5,210) = 2.57$, respectively. The organization x groups, groups x movement distances and movement distance x trial blocks interactions were also significant at $p < .025$, $F(7,42) = 4.15$, $F(8,168) = 6.19$, and $F(20,840) = 2.38$ respectively.

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Insert Table 2 About Here

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The AE results of Phase I replicated previous findings associated with the effects of movement organization. However, in Phase II, the previous findings with respect to the switched limb paradigm (Wallace, 1977) were not replicated. Tukey's post hoc analysis indicated that when either limb or direction was switched, errors increased relative to the group where criterion and reproduction attempts were identical. Such a finding weakens the rationale for using the switched-limb technique in the present context. However, should organization be potent enough to overcome the deficit incurred when direction and/or limb is unreliable, support for localizing/ organizational benefits in retrieval processes may be indicated.

That is, if the cues used to encode location information are made remote from its reproduction, performance would then reflect the rule or strategy for making the reproduction attempt.

Such support was found in the organization x groups interaction shown in Figure 2. Here, sequential and random groups did not differ in those conditions where the same limb was used for reproduction (Sa-Sa) or when the same direction was used (Sw-Sa). However,

Insert Figure 2 About Here

when both limb and direction were switched (Sw-Sw) the sequential group performed at about the same error level as the same limb, switched direction group (Sw-Sa) while the random group's error continued to climb. If organization were an encoding or storage benefit, the sequential groups in this latter phase should have performed with less error in all switching combinations. However, if the effect is localized in retrieval processes then the benefits of organization would be demonstrated in those conditions where the usual cues were unreliable. In fact, there was no benefit of organization where the limb-specific sensory consequences of the movement were available or when direction and distance were reliable cues. When these cues were unavailable or distorted the presence of organization attenuated the deficit expected.

In CE scores of Phase I, movement distance and trial blocks were significant at $p < .25$ as well as their interaction, $F(4,168) = 11.58$, $F(9,378) = 2.49$, and $F(36,1512) = 2.47$, respectively. The movement distance effect was caused by a significant undershooting at the 20 cm target. The trials effect reflected the decreasing error expected with learning. In Phase II, the switched limb/direction groups main effect and the groups x movement distance interaction were significant at $p < .025$, $F(2,42) = 5.06$ and $F(8,168) = 9.29$ respectively. The effects in Phase II were due to increased undershooting in the switched-limb, switched direction group which reproduced from the opposite direction. As in Experiment 1, CE scores were quite small, ranging from -.64 to .14, reflecting a possible floor effect. The benefit of organization was not distinguishable in error scores indicative of directional bias. It would seem that while organization reduced the magnitude of error it does not affect the tendency to under- or overshoot differentially.

## General Discussion

The purpose of these experiments was to better define the locus of organizational benefits in memory processes. Previous research indicated two processes in particular, encoding (Nacson, 1973; Nacson, et al., 1973, Gentile & Nacson, 1977) and storage (Diewert & Stelmach, 1978). The result of the present experiments suggest some modification of these contentions. The argument has been made that the greatest

benefits of organization are effected in retrieval processes. Consider together the following points:

1. Subjects must be consciously aware of the organizational structures present in order to benefit from them an awareness usually achieved through instruction (Gentile & Nacson, 1977; Diewert & Stelmach, 1978).

2. Subjects who are allowed to impose their own order on the information choose a sequential order and perform with greater accuracy than those constrained to use the experimenter-presented organization (Diewert & Stelmach, 1978). Both this point and the previous one seem to highlight the cognitive input of the individual in the generation of the reproduction attempt.

3. There is no beneficial transfer of organization when one changes from an organized context to a random one. Similarly, the order under which previous learning occurred is not as critical as the current order under which the individual is performing. The principle of encoding specificity does not apply (Experiment 1).

4. There is no differential benefit of organization when varied retention intervals are used, a strong argument against a "strengthened memory representation" being the locus (Experiment 1).

5. There was no differential benefit to organization when other perceptual cues were available in the switched-limb paradigm, a technique designed to separate encoding from response generation.

However, organization did attenuate the deficit seen when the relationship between the individual's spatial coordinate system, the target and the physical context is made unreliable (See Experiment 2). These five points suggest that organization facilitates the retrieval strategies or rules actively used by the individual to access and retrieve information from memory for the purpose of response generation.

At this point it would perhaps be beneficial to expand on the earlier explanation of memory processes to examine just where and how organization may have the greatest effect. As mentioned previously encoding is comprised of perception of information and its subsequent translation or recoding (Diewert, 1977). That organization would enhance perception is unlikely since this manipulation would not heighten the feedback from peripheral receptors or affect transducers differentially. However, there are a number of ways that the translation or abstraction process could be affected. By noting similarities, redundancies and/or regularities incorporated in some organizational framework, the individual could enchance the translation process by reducing the amount of information required to specify an item unambiguously. If such a reduction were accomplished a secondary benefit would be seen in an increased storage capacity, however, the locus of this benefit would be in storage. The present experiments do not address this storage capacity notion since only five items were used.

A second and more critical alternative may be a difference in precision. That is, would having an organized presentation aid the translation process by decreasing the uncertainty of the abstract form in specifying the target item? The learning phases of each of the experiments cited here seem to indicate that this is the case, that having encoded information sequentially, accuracy is improved. Switching in the latter phase of testing to a random order should have had little effect on the originally encoded targets. Yet differences did occur in Experiment 1 suggesting as already stated that some later process was responsible for the observed differences and that encoding specificity (Tulving & Thompson, 1973) did not apply to organization. That aspect of the encoding process which indeed may facilitate later processes is the formulation of a rule or strategy which when made available to retrieval processes achieves the observed benefit.

Storage processes would seem least likely to benefit from movement organization. If the target can be specified in two ways, e.g. detailed and specific versus abstract and general, no rationale - trace decay or interference theories (Stelmach, 1974) - suggests a stronger or more resilient memory representation due to organization. Although the interference viewpoint might suggest that a simple, abstract code would be less susceptable to disruption from interfering events than the complex, detailed

representation, no retention benefit was found in Experiment 1. Furthermore, if the benefit were truly localized in the storage of the target information than sequential and random groups would be expected to diverge over time. Instead it is common to find the groups differing after only 1 or 2 trial blocks and either maintaining the initial difference or eventually converging.

There appear to be a number of ways that organization may possibly aid retrieval processes, which in this context includes a search through memory for the target and generation of a response to reproduce the target. Two searches are involved in the linear positioning task, the first specifying grossly which of the five target items is required. Organization makes possible a content-addressable search (Massaro, 1975) where the label directly communicates location in memory and in which mnemonic devices or labelling would be most useful. In the present paradigm the benefit to this type of search is minimized by the criterion movement immediately preceding the reproduction attempt and the use of a relatively small number of targets. The second type of search requires one to distinguish one point in space from the infinite number of points nearby. It is this point, the target, which is specified by an abstract code and this discrimination that determines accuracy.

Organizational principles used to generate rules or strategies to specify a target in memory may also be used to guide the reproduction

attempt. An example might be: Let O = origin (starting position), let D = the distance between targets, then O + D = Target #1, O + 2D = Target #2, etc. such that O + (Target #)D would specify all targets in these experiments. In the switched-limb paradigm a simple transformation, O + (6 - Target #)D, could be used to guide reproduction attempts. Not only could such a rule be used to generate the response by providing the desired values for the variables in the equation; but such a rule could also be used to test the correctness of the attempt (Stelmach & Szendrovits, Note 1), e.g. test whether the abstract code for the location chosen satisfies the equation specifying the desired target. Using a rule or code in this way could be quite helpful when the criterion information differs greatly from the reproduction attempt as is the case in the switched-limb technique. When this manipulation was used, organization was beneficial only when other cues (limb, direction, distance) were unusable or distorted.

Gentile and Nacson (1977) maintained that individuals used stimulus properties such as "spatial relations, contextual relations, temporal patterns, and other stimulus redundancies" (p. 14) to develop rules of encoding, their logic being that motor recall was dependent on the encoding process. We would concur that organization provides a rule, e.g. their "sequential-incremental" rule where both a relation (sequential) and a code (add a constant distance) were used.

However, we propose that the abstraction processes involved in encoding information are responsible for or aid in providing the rule or strategy used later in the retrieval of the information. The reasoning for such a suggestion is that if encoding is organized, the rule or strategy employing that organization is at least available and usable by subsequent processes; but if organization does not also benefit retrieval processes, organized and unorganized groups would be undistinguishable on the basis of performance. The present data suggest that retrieval processes may benefit independent of encoding processes.

## Reference Note

1. Stelmach, G.E., & Szendrovits, L.D. Error Detection and Correction with Organized Movement Sequences. Manuscript in preparation, 1980.

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[1] Since Wallace (1977) found that the reproduction accuracy of the right and left arm were equal when direction remained invariant this condition was omitted from the experiment.

TABLE 1

Mean Absolute Error in cm of Organization

by KR Interaction, Phase I

| | KR | No KR |
|---|---|---|
| Sequential | 1.66 | 1.96 |
| Random | 1.87 | 2.10 |

TABLE 2

Mean Absolute Error in cm for Organization

by Switched Limb-Direction Interaction

| | Phase I | | Phase II | | | | | |
|---|---|---|---|---|---|---|---|---|
| Trial Block# | 10 | | 1 | 2 | 3 | 4 | 5 | 6 |
| | | Sa-Sa[a] | 1.75 | 1.97 | 1.71 | 1.76 | 1.73 | 1.37 |
| Sequential | 1.27 | Sw-Sa | 3.32 | 2.59 | 2.33 | 2.85 | 2.95 | 2.66 |
| | | Sw-Sw | 2.59 | 2.11 | 2.36 | 2.08 | 2.35 | 2.57 |
| | | Sa-Sa | 1.76 | 1.89 | 1.70 | 1.95 | 1.91 | 1.52 |
| Random | 1.49 | Sw-Sa | 2.72 | 2.47 | 2.49 | 2.88 | 2.24 | 2.61 |
| | | Sw-Sw | 4.46 | 3.42 | 2.83 | 3.34 | 2.92 | 3.51 |

[a] Sa-Sa = same limb-same direction

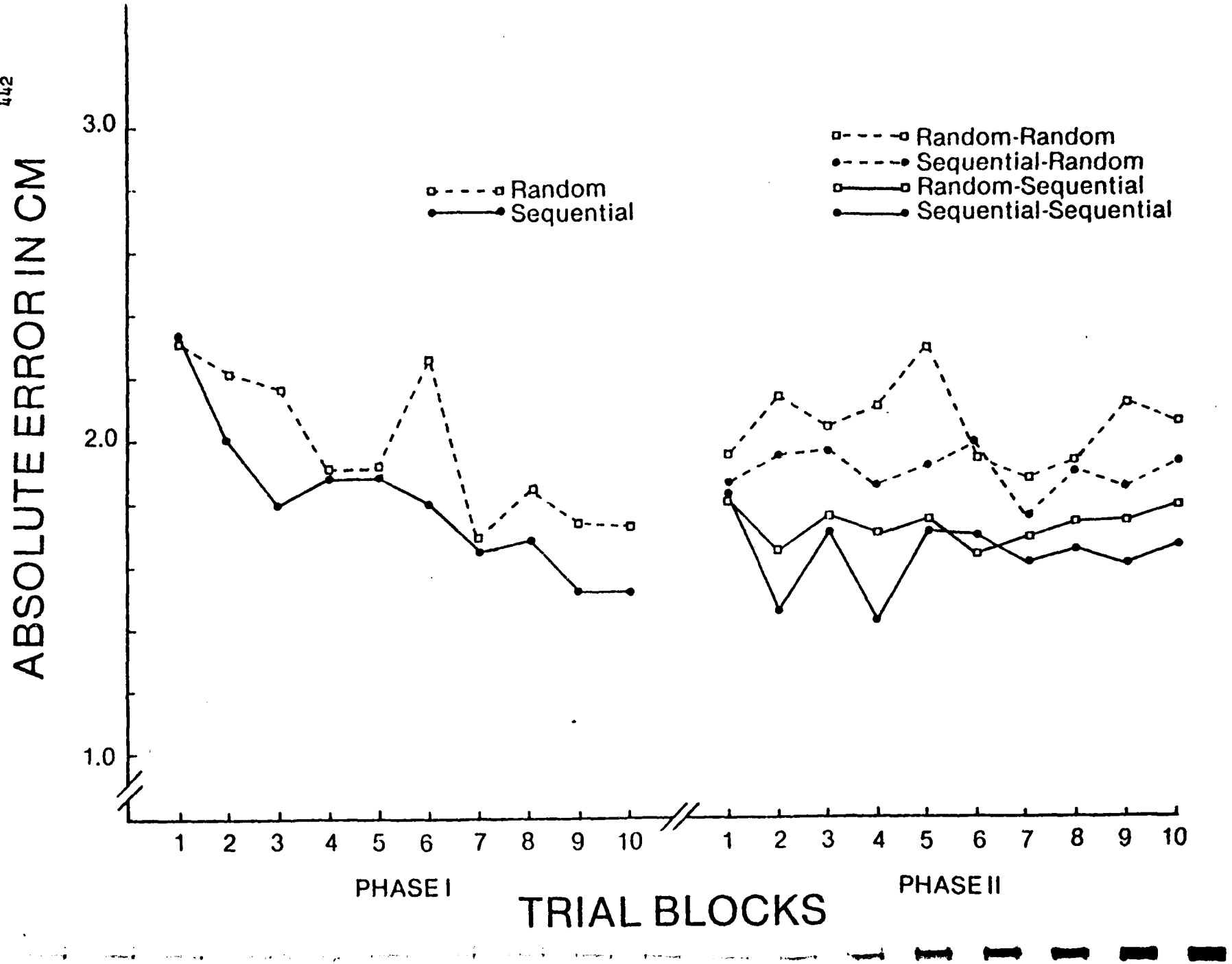
Sw-Sa = switched limb-same direction

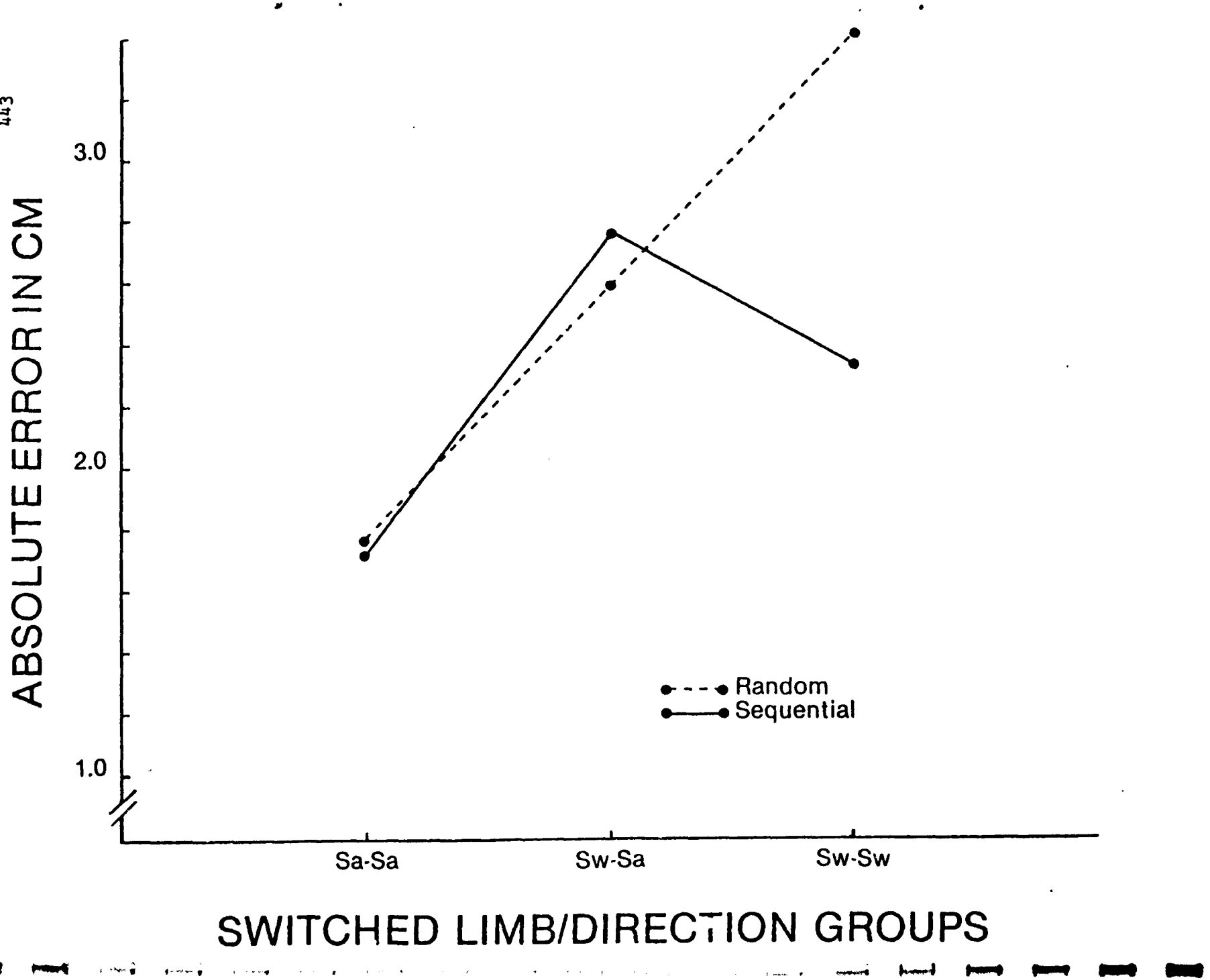
Sw-Sw = switched limb-switched direction

## Figure Captions

Figure 1. Absolute error in cm for random and sequential groups in the learning phase (Phase I) and for the organizational transfer groups in the retention phase (Phase II) of Experiment 1 is shown. Each trial block represents the mean error of 5 reproduction attempts, one at each of the 5 target locations.

Figure 2. The interaction of organization groups with the switched-limb manipulations for Phase II of Experiment 2 in absolute error: Sa-Sa = same limb, same direction; Sw-Sa = switched limb, same direction. Sw-Sw = switched limb, switched direction.


ABSOLUTE ERROR IN CM
3.0
2.0
1.0
Random
Sequential
Random-Random
Sequential-Random
Random-Sequential
Sequential-Sequential
1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 6 7 8 9 10
PHASE I
PHASE II
TRIAL BLOCKS


ABSOLUTE ERROR IN CM
3.0
2.0
1.0
Random
Sequential
Sa-Sa
Sw-Sa
Sw-Sw
SWITCHED LIMB/DIRECTION GROUPS

# Part IV

# Current Issues in Motor Behavior

# and

# Prospects for the Future

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## ABSTRACT

Three vitally important areas in motor performance research are presented with especial emphasis placed on the level of their current understanding and on the directions it is believed they should take in order to maximize not only conceptual understanding but also practical application in systems design, training and actual performance. The first area is that of control theory where it is revealed that contemporary models or analogies, for the most part, do not adequately describe known or hypothesized characteristics of motor organization. Descriptions of more appealing systems are provided and emphasis is given to the use of control theory as a broad research paradigm for enhanced conceptualization and experimentation. The second area addresses the specification of action; in particular, the means of the realization of overt volitional acts from abstract plans, and the parameterization of movements are speculated upon. The final section discusses the topic of motor skill automation with special regard to its labored empirical progress, and to its relationship with volition and attention. The overall theme of the review is not to express the explicit practical utility of these topics but is rather to recognize the issues which, for a number of reasons have failed to bear practical fruit in the past (thereby attempting to make both researchers and flight instructors aware of their existence) and to offer some tentative guidance regarding issues which, when more completely comprehended, will be of use to the Air Force and others interested in maximizing human performance.

# INTRODUCTION

While the psychological and physiological basis of motor performance has interested researchers and those people or institutions which seek to gain serviceable information from research for many years, both areas have witnessed a sudden expansion and increased dynamism recently. There are several reasons for this new interest: First, there has been an increased realization that motor skills have a rich cognitive component intermediary to perception and action (although Air Force research programs have concentrated on such considerations to a notable extent). Second, those interested in motor performance and those who have been traditionally linked only to psychology have developed, out of mutual necessity, a dialogue with the neurosciences. Such multidisciplinary intercourse has already begun to create new conceptual understandings and opportunities. Third, artificial intelligence has developed techniques that enable computers to exhibit aspects of intelligent behavior and has made insightful contributions to the comprehension of the nature of multipurpose control systems. The utility of such research in defense related institutions should become apparent. Finally, motor skill research is no longer shackled by the requirement of practical applicability and has turned toward the processes that underlie skilled performance. While such a theoretical emphasis may not satisfy the immediate demands of instructors and teachers who are searching for ideal methods by which trainees can learn tasks, it may be of some comfort that only by such an approach now will applied benefits be forthcoming.

The thematic shift away from research on skill acquisition and learning variables toward motor control processes has taken place because learning cannot be adequately characterized without first understanding the structural and functional means of control. It appears that addressing processes rather than products is a more basic task for research. Indeed, such a change is radical, especially since motor performance research was initially shaped by the attitude that learning is the primary aspect of the skill situation that any instructor or trainer should be concerned with. Previously, the conceptual structure for motor performance research was shaped by the overriding view that improvement in task performance (whether measured by speed, reduction of error, or response consistency) was the sole criterion for successful learning. This approach produced voluminous amounts of empirical research that conveyed little knowledge regarding the acquisition and retention processes of human performance.

If any concept worthy of note that has emerged from the research in skilled performance over the years, it is the realization that the human as a behaving system is extremely complex. Yet, the history of scientific inquiry has taught that the main path to generality and elegance is to search for measurable properties of behavior where the observable phenomena take on especially simple forms. After many years of attempting to simplify motor behavior through reductionistic paradigms, the emerging contemporary theme is that a complex system cannot be understood as a simple extrapolation from the properties of its elementary components and that this form of scientific inquiry detracts from the integrity of the system that is being studied. When viewed mechanically, the human organism is a multisegmented, multilinked system whereby movement

of one segment can influence the motion of an adjoining segment in a variety of ways. The plasticity, flexibility and intricate organization of an acting human presents researchers with a multi-layered puzzle possessing an infinite number of pieces and combinations.

From the foregoing realizations, there is a trend emerging in all motor performance research which appears to favor holistic and interdisciplinary approaches and which considers the entire system in its attempts at understanding. There is a definite move toward more descriptive studies that focus on phenomena and away from "experiments on experiments". This expansive outlook is also perhaps an indication that the motor behaviorists, who in the past pursued relatively parochial lines of research, have developed a common language with their colleagues in cognitive psychology, systems engineering, biomechanics and the neurosciences. Of greatest import is the potential of a multidisciplinary approach to lead the theorist and practitioner further toward some solution of the puzzle of skilled human performance.

Our feeling is that if the area is to advance it must be cognizant of the holistic and ecologically valid perspectives. These perspectives are quite broad and it is not so much the intention of this review to cover all possible applications of these perspectives as it is to offer a guide for future research concentration. We have chosen three issues-- clearly, not an exhaustive list-- which we believe to be central to progress in the area of skilled motor performance. The remainder of the chapter will be concerned with introducing the chosen topics, briefly explaining the present status of each and speculating on their pertinence and potential for further investigation.

In the first section, control theory is introduced as a vehicle to enhance future conceptualization and experimentation. The viability of this perspective permits interdisciplinary interaction, providing a framework capable of encompassing the entire system and generating eloquent simulation techniques to test and compare theoretical models. However, since control theory provides only a conceptual referent for examining motor performance, the second part of the chapter deals with the specification of action. As such, we speculate about the translation of higher level codes into the language of muscle dynamics, firstly, in terms of action plan realization and secondly, at a less-abstract level of discussion, with regard to the metrical and structural specifications between control levels. Lastly, skill and action automation is discussed in the light of the slow and difficult progress which is being made in the area. A number of contemporary ideas about automated skill are highlighted and future experimental possibilities, especially those utilizing skilled actors in normal, and/or natural situations, are offered.

## FUTURE DIRECTIONS

### Control Theory

Motor control has moved to the forefront as a topic of research interest in many areas interested in human performance. It has evolved to the extent that commonly used, though controversial, models are inadequate at addressing the questions control theorists ask. Their inadequacy lies primarily in their simplistic portrayal of the human motor control system and the limited investigation prescribed by such a view. The more common representation is that of a hierarchical, single-level control system in which movement is the output resulting from the execution of motor commands issued from

a single command generator. Conceptualizing the motor system in this way has led to the focusing of investigative attention on events occurring prior to specification of the response as is seen in most information processing models (Massaro, 1975; Welford, 1968). An example of this type of model is seen in motor programs, used by Henry and Rogers (1960) to describe control of rapid movements, and subsequently popularized by Keele (1968). At that time, Keele defined a motor program as a centrally stored, pre-structured set of motor commands specifying all parameters of the movement but, he has since presented a more palatable and less detailed and specific version in which the sequence of movements is represented in the motor program. However, when precision is required or corrections are necessary, it is argued, allowance is made for closed-loop adjustment.

While the motor programming notion has engendered much research for some time (Keele, 1977; Klapp & Irwin, 1976; Sternberg, Monsell, Knoll & Wright, 1978), it has been a less than satisfying analogue for movement control. The complexity of the human motor control system far exceeds the explanatory capacity of this concept. The rigidity of motor programs cannot explain how muscles may vary their functional roles about the same joint nor why the innervational states of an individual muscle and the movements it produces relate equivocally (Turvey, Shaw & Mace, 1978). When one considers the possible degrees of freedom (Turvey, 1977) for humans involved in skilled movement, it is difficult to conceive of one structure (the executor) specifying the exact timing and combination of muscle contractions for all possible movements. Such a notion places considerable responsibility on the executor, prescribes total dependency

of any lower portion of the system, and suggests a vulnerability to disturbances and malfunctioning not characteristic of the human performer.

Control Theory Perspectives

These paradoxical control problems unaddressed by single-level control models suggest a need to thoroughly reassess our traditional views of how the higher brain centers control coordinated movement by the adoption of a conceptual framework that stresses the entire behaving system, unencumbered by methodologies and "hardware" considerations (Stelmach & Diggles, 1980). The framework we believe most useful for understanding the theoretical positions emerging is that of control theory, derived from systems analyses (Toates, 1975). Control theory can be viewed as a methodological or operational paradigm, focusing on the interactive behavior between or among the components of the physical system where a system is defined as an interconnection of components forming a configuration to provide a desired response (Metz, 1974). Control theory is more than simply a methodology, it is an idealogy for studying "how things work", and by its nature draws on many disciplines for application. A control theory perspective aids in conceptual thinking and provides a basis for constructive criticism and functional evaluations.

There are several facets of control theory which recommend it as a framework for understanding motor performance in particular. As previously mentioned, an increased awareness of the complexity inherent in the control of action has served to demonstrate the inadequacy of many simple models in the literature. A control theory framework considers the entire system, attempting to represent complexity while at the same

time refining it to a more digestible quality. Although it is an integral part of the engineering sciences, control theory is not bound to any one discipline, its utility is universal where physical systems are identifiable. The common language provided by control theory promotes and facilitates interdisciplinary exchange and the awareness that the principles educed are not dependent on the physical "hardware" of the system. Thus, it furnishes a superstructure for interpreting and comparing findings from multiple sources.

Classifications

There are many diverse types of control systems, each with particular advantages and disadvantages as far as the type of control they exert is concerned. We have chosen three characteristics by which control models may be categorized that go beyond simple open- and closed-loop notions. The first characteristic addresses the basic organization of the system and specifies the direction of control. The form of organization addressed here is hierarchical where higher centers exert control directly or indirectly on lower structures or mechanisms. Feedback would not qualify as control in this sense, since it is only meaningful relative to the desired outcome, thus feedback loops can be included in a hierarchy without breaching the "top-down" flow of command.

The second categorical distinction is related to the number of levels of transformation information must pass through between the system reference signal and the achievement of the goal state. A transformation in this sense should be thought of as both refinement as in increasing specificity and alteration due to additional inputs at other levels. For simplicity's

sake, the number of levels a system may possess has been dichotomized into single-level and multilevel categories.

Still a third trait operationally distinguishes control processes into a meaningful dichotomy: lumped and distributed control. This particular distinction focuses on control within a level of the system defined and the function of the structures at that level. A lumped model is defined where control processes or functions are homogeneous across structures at a single level. Examples of lumped systems can be found in most information processing models in which one structure is posited to operate on input at any given level. In a distributed control system, function at any one level is spread or distributed among a number of structures which may interact to achieve the desired output (Arbib, 1980). Consequently, a distributed system does not require an executive command generator to initiate and control movement. An example of distributed control is seen in the context of industrial control systems, where a hierarchy of loosely coupled computers manage the optimization of production by sharing responsibilities to achieve overall plant goals. (Kahne, Lefkowitz, & Rose, 1979).

Each form of control possesses characteristics which are reflected in the theoretical models that are subsumed under it. As models are classified under a particular form of control, the advantages and disadvantages associated with that form may be anticipated in the model. Thus, one may evaluate the control capability of existing models based on their form of control. It should be noted that a taxonomy such as that layed out here is an operational convention to aid in theory comparisons and evaluation, thus, it is certainly arbitrary, and overlapping

categorizations will occur due to the broad range of theories. For example, there are theories which address the entire behaving system and those which attempt to model some discrete aspect of the system; both can possess varying degrees of complexity and detail. Regardless of the scope of their intended description, models can be classified by their control characteristics. Thus, multilevel lumped or distributed control theories may encompass systems that vary widely in their control responsibilities; for example, the firing of a single neuron versus the regulation of a gross movement.

Exemplars

In opposition to the simplistic single-level notions of movement control, the concept of functional groups of muscles, be they synergies (Bernstein, 1967); motor schemas (Arbib, 1980); spinal automatisms (Shik & Orlovsky, 1976); or generators (Smith, 1980), have been posited as intermediate levels of control to describe the meaningful units by which the central nervous system specifies movement. Early on, Bernstein (1967) proposed these intermediate steps between the higher centers and individual muscle contractions. He suggested that movement may be specified in terms of muscle linkages; linkages being defined as a group of muscles that commonly work in synergy. This view, in one form or another, has been expressed by a number of people (Easton, 1972; Gelfand et al., 1971; Greene, 1972; Turvey, 1977). Easton (1972) more specifically suggested that a considerable amount of motor coordination was based on a repertoire of reflexes. Muscles engaged in associated movements could be functionally connected by combinations of reflexes or coordinative structures which could be activated by a single command of either central

or peripheral origin. The notion of coordinative structures invoked by Easton refers to the pattern of connections between interneurons and other interneurons or motoneurons that resemble those patterns elicited by reflexes (Easton, 1978), and was arrived at through observation of quadrupedal gaits, some athletic and art forms (Fukuda, 1961) and neurophysiological findings (Hellebrandt, Houtz, Partridge & Walters, 1956; Orlovsky, 1976). Further support for these functional muscle combinations is derived from the presence of interneuronal networks which may be activated to produce stereotypic movements and segmental reflexes. The autonomy connoted by this subsystem would be curbed slightly by the necessity of a smoothing or tuning function to choose and fit appropriate sets of muscles to achieve coordinated, volitional movement (Greene, 1972).

Central systems using the mechanisms proposed above fall under the rubric of multilevel systems where transformations of the movement command do intervene between intention and performance. The advantages of multiple levels of control over single-level ones include a reduction in the size and complexity of the command and the alleviation of the computational burden on the high level "executor" by delegation of minor computation and processing to lower levels. However, these models are still simplistic in a control sense because they suggest that functioning is lumped within levels. The disadvantage of lumping control in this way is the loss of plasticity and flexibility attainable if control is interactive at a given level. Subsystems may not compensate for each other except through the next highest level of control. Lumped models of the central nervous system also require an executive controller

or "command neuron" (Rosenbaum, 1977) to initiate commands, resulting in a rigid and vulnerable control system. In some cases, the lumped model may be a simplification of a more complex, distributed model but the cost of simplicity is the elimination of plasticity and flexibility. One factor contributing to the use of lumped models is the, as yet, poorly defined "hard wiring" of the system. When more is known about the interactions and interconnections of the central and peripheral nervous systems lumped models will presumably become less common.

To circumvent the shortcomings of behavioral models falling in the lumped category, it appears necessary to postulate not only vertical interaction in the nervous system but horizontal interaction as well. In support of horizontal interaction, Soviet investigators have focused on the spinal cord as a complex mediator between supraspinal influences and muscle contraction (Berkinblit, Deliagina, Feldman, Gelfand & Orlovsky, 1978; Gurfinkel, Kots, Krinskiy, Paltsev, Feldman, Tsetlin & Shik, 1971; Gurfinkel & Paltsev, 1965; Shik, Orlovsky & Severin, 1966). For the most part, these investigators view muscle synergies, as did Bernstein (1967), as mechanisms for simplifying the control of movement by functioning as the external language of movement and the internal language of the nervous system. A number of investigators systematically examined the communication and interactions of subsystems involved in preparing a complex, kinematic chain such as the body for movement (Belenkii, Gurfinkel & Paltsev, 1967; Gurfinkel & Paltsev, 1965; Paltsev and Elner, 1967). Gurfinkel and Paltsev (1965) demonstrated the presence of contralateral influences in the spinal cord when observing that a knee jerk on one side altered the state of the segmentary structures of the opposite side by

evoking both patterns of facilitation and inhibition depending on the time course of the task. Belenkii, Gurfinkel and Paltsev (1967) also reported anticipatory activation of some muscles of the lower limbs and trunk involved in maintaining equilibrium. Recordings indicated that neural activity preceding movement was elicited not only from alpha motoneurons but also from the interneurons of the spinal segment. It appears that supraspinal processes do not simply send direct movement commands but that their basic role is the "appropriate rearrangement of the interaction organization of the individual subsystems at the spinal level" (Gelfand et al., 1971, p. 336). Thus, high level processes which prescribe the interactions of subsystems can be seen to implement feedforward and achieve tuning. It is the interactive and cooperative nature of these spinal processes that places them in the distributed category.

The findings reported suggest that movement is controlled by a multilevel, distributed system where control is diffused across several structures that interact within and between levels to arrive at an output. In this context a single "command neuron" or executor is not requisite but may be replaced by the cooperative effort of a number of structures or collection of neurons. Thus cooperative computation, as Arbib (1975) terms it, is achieved through both vertical and horizontal interaction of neurons. This type of control offers an explanation of the adjustments seen in movement to compensate for variations in starting position, unexpected disturbances, and injury to a subsystem. In doing so, the system's reliability is greatly enhanced.

The advantages preferred by models of distributed control are convincing proponents of this concept. The flexibility and plasticity of such models closely resembles that witnessed in human performance and illustrates the adaptability of which distributed control is capable. However, there are disadvantages to distributed control which may detract from its optimality and yet add to its veridicality. When control is centralized through a high-level controller with all information available, better performance, relative to specific situations and purposes results. However, this achievement is at the cost of flexibility, reliability and an extraordinary increase in responsibility of the single controller. When control is decentralized, as in a multilevel distributed model, greater flexibility is achieved through interacting systems, but there is also the potential for errors with each interaction, much like residual noise in the system. Although such noise would not be great enough to result in a system failure, it would increase the variability of the output. Noise-produced variability in this context could explain the observation that humans never perform a task exactly the same way twice.

Perhaps the greatest disadvantage to the concept of distributed control is the difficulty one encounters in trying to study it. The possible interactions and potential sources for input present the investigator with a Gordian knot, difficult to unravel and difficult to retie. The scarcity of research efforts directed at testing this model assert the reluctance some may feel in using such a model. We feel that control modeled as a multilevel, distributed system is worth the effort of examination. Phenomenologically, convincing parallels

have already been identified between the human nervous system and this type of control, and future investigation should be aimed at empirical substantiation.

In the past, certain aspects of control theory have been applied to the study of motor behavior. Input-output relationships, block diagrams, and "black boxes" were commonly used conventions in systems modelling. This elementary application is in some ways responsible for the simplicity of earlier models. The true potential of a control theory perspective has not been realized due to this rather eclectic approach to its adaptation. If we are to progress toward more veridical representations, the objective of simulation techniques, the models built must reflect more closely the complexity of the system they are to represent. We believe control theory has much to offer in the modelling of motor control systems as stated previously; and as will be seen in subsequent sections, it offers a logical framework for consideration of specific control mechanisms. We hope that this brief exercise in the evaluative capabilities of control theory has demonstrated the utility and power of such a perspective and has encouraged its future adoption.

## Specification of Action

### Plans of Action

One of the most important issues to be addressed in motor control is the interface of abstract representations, from which actions are constructed, with movements. This interface requires the translation of a higher level code to the language of muscle dynamics. The propogation of this control signal seems to be one of the most natural, albeit perhaps most elusive, objects for investigation since scientists are continuously

seeking optimal and valid solutions for complex systems. Knowledge of the mechanisms used for the development and transformation of economical and expedient control signals would certainly add to optimal understanding of the performing human. Toward this end we shall examine transformation processes for a plan of action, tuning, and finally the language of muscle dynamics in an effort to propose some questions that we believe can stimulate and guide future research.

Any theory of action must account for the obvious translation of intentions into purposeful movement. This is made possible, at least conceptually, through a plan of action. We propose that a study of action plans, per se, will not further the understanding of motor control but that a study of how the process required to translate these abstract representations into action will invite a future direction for inquiry.

Psychologists primarily have been the ones to invoke a variety of explanations to describe plans of action in an attempt to explain purposeful interaction with the environment. Conventionally, plans of action are described as general instructions prescribed for the regulation and integration of muscular coordination (Miller, Galanter & Pribram, 1960; Norman, Note 1; Pew, 1974). Three attributes are characteristically ascribed to action plans. First, plans are derived from intention. Second, plans are general representations of action and not detailed specifications. Third, they contain information concerning both the appropriate sequencing of movements and their temporal characteristics as they relate to the serial nature of the act. Unfortunately, these explanations remain in a conceptual format and have not moved into an experimental setting, a transition which is necessary if

practitioners are to understand conceptually and behaviorally the course of action. Since this has not happened, nor is it immediately likely given the "slippery" nature of these constructs, we propose that a more fruitful approach would be to study the process by which these higher level control signals carry out their control functions.

Tuning

The development of action plans into a precise regulation of movements requires the translation of crude general commands to specific muscle activation. Assuming that a plan of action may be implemented through the process of tuning two immediate questions must be answered. How is tuning effected and where is it implemented? It has been proposed that tuning is accomplished through feedforward and feedback mechanisms while the implementation seems to occur at an intermediate level of control, functional muscle groups (Arbib, 1980).

It seems quite clear that a composition of coordinated movements is not controlled by commanding single muscle contractions. The advantage of this intermediate level of control, of course, lies in reducing the degrees of freedom of the system in its complex interaction with the environment while simultaneously reducing the load on memory. Physiological evidence for the presence of functional muscle groups has been available, as a result of Soviet research, for a number of years. Shik and Orlovsky (1976) found that the basic pattern of stepping could be generated by the spinal cord without input from the brain. This spinal automatism controls phases of activity of muscles in the stepping cycle while the brain influences the overall level of muscle activity. The unmistakable presence of interlimb reflexes and the central coordination of limbs during locomotion indicated a higher

level automatism responsible for these events. Easton (1978) supplied a particularly appealing description of how such functional muscle groups could operate, which was alluded to earlier. Briefly, movement commands activate reflex centers which, in turn, activate groups of monorneurons and/or interneurons. Once the pathways are facilitated, the central nervous system issues a general excitatory command to all motorneurons but triggers only the facilitated ones. The product of the reflex centers are thought to be fitted together and smoothed by a set of tuning transformations. Sources of input are accessible from direct cortical control of motoneurons, from afferent feedback, and from reflex recruitment.

Emerging from the neurosciences also comes the realization that muscles engaged in associated movements, which may be functionally connected, could not be controlled simply by combining stereotypic actions. Although movement commands may activate functional muscle groups, coordinated volitional movement would require a smoothing or tuning function to choose and fit appropriate sets of muscles (Easton, 1972). Greene (1972) specifically describes tuning before movement as selecting an appropriate operating characteristic (feedforward). The highest control center selects an appropriate combination of movements that appears to provide the best fit for the desired outcome while transformations at lower levels shape this combination into a more precise approximation through feedback. The parameters that appear to be controlled in the tuning process relate to selected functional muscle groups and their temporal characteristics.

A further elaboration of tuning is provided by Arbib (1980). Coordinated control programs schedule and coordinate simultaneous actions through the use of feedforward and feedback mechanisms so that successive actions are smoothly phased in order. Several ideas have been developed in an attempt to explain how plans of action are translated into coordinated movement, the most popular of which considers action plans to be implemented through a tuning process which in turn exerts its effects on functional muscle groups to orchestrate voluntary movement. Although these ideas are more characteristic of a complex behaving system, they are in large part speculative and therefore warrant a great deal of further empirical scrutiny. For example, those interested in skill performance might ask how the system maps one control signal to coordinate many signals; that is, how humans perform a single operation that controls independent components in a very detailed and prescribed manner, and at which levels of the nervous system these transformations take place. We believe that future research will certainly revolve around these new issues and related questions.

## Parameterization of Action

### The Language of a Control System

An additional contemporary issue is one which addresses control problems at closer proximity to the surface structures than those commented on thus far. As a matter of necessity, control systems research should be married

to work aimed at defining the parameterization, or at least the degree of parameterization, of action. At least two reasons justify the necessity. First and foremost, a control system, in and of itself, cannot adequately describe action; it merely provides a framework or environment in which action, given suitable context, could occur. Clearly, a control system is unusable if its software is neither described nor appropriate since it then has no means of control; it would be like a machine with no operating instructions. Furthermore, the greater the controlling influence assigned lower centers, given their functional flexibility, the greater the need for specific understanding of parameters. One way to analogize parameterization is to consider the control system, whatever its characteristics, and the "language" with which it must realize, from a non-motor plan of action, an overt motor act. The language can be considered the most mutually informative, concise and immutable instruction relayed from one control level to any other. The language of one pair of control structures may be different from that of another pair, but over the entire system, structures which converse with each other do so in a common language.[1] For example, in a hypothetical control system movement force is specified by an executive structure A. Structure B, responding to it, integrates the quantity and obtaining a velocity specification which it might relay in turn to structure C. Through further quantity integration C is therefore capable of obtaining a displacement value from A's original force specification by dealing only with B in their common 'language'.

The second reason for improving the understanding of this language is the result of traditional motor behavior theories' inherent inability

to represent known functional characteristics of the nervous system. Motor programs (and open-loop systems of similar ilk), additionally, are rigid and energy-expensive even as theoretical models because of their single-level lumped control characteristics. Mounting physiological and behavioral data (see Stelmach and Requin, 1980 for a contemporary anthology) are suggestive of a multilevel control system with distributed and perhaps free-dominant characteristics (Turvey, Shaw & Mace, 1978). Being address-specific, motor programs are cumbersome and top-heavy to the extent that even the simplest acts would, it would seem, overload the executive's storage and specification capability. In terms of the analogy, rather than determining which entity of the 'vocabulary' would permit initiation and partial completion of any act, a motor program would seem to need a pre-determined and correctly ordered number of different 'letters', a situation certainly uncharacteristic of an efficient and effective control system (and one also failing to resolve the degrees of freedom problem mentioned in the preceeding section). In addition, both open-and closed-loop theories place imbalanced priority on efference (open-loop) and afference (closed-loop) when such a dichotomy is becoming increasingly redundant (see Evarts, 1971; Kelso & Stelmach, 1976; Kelso, Holt, Kugler & Turvey, 1980; for discussions).

Motor Programs

Recently, and in the light of more convincing evidence, the concept of motor programs has been revised. Schmidt (1979), for example, has promoted the idea that a motor program should now be regarded as an abstract memory structure which contains certain generalized and invariant properties but which, at some stage of action realization, requires the specification of other parameters in order to allow the act's unique characteristics to evolve (shades of 'vocabularies', one suspects).

One obvious need in motor performance research is to determine whether every metrical and structural prescription is context-specific and dependent upon the muscle involvement or movement characteristics. In addition to pursuing this problem, other directions of research need to be examined; namely, the appearing arguments and models which have been proposed with regard to the physical and dynamic properties of muscle. Suffice to note here that at least one reason for their appeal is that muscle is the final component or filter through which all motor output must pass (Cooke, 1980; Turvey, 1977).

The research on innate activities such as gait, again primarily by the Soviets, reveal that there may indeed be centrally programmed parameters which are invariant over changes in the stepping pattern. Shik and Orlovsky (1976) noted that increases in locomotion speed are only the result of changes in force application during the stance phase and not in the phasing (relative timing) of the limbs. Grillner (1975) has provided a model which considers sequencing and relative timing to be invariants in the production of action, and Schmidt (1979) has suggested that relative force within a sequence might also be specified in an act's abstract representation. There is not a great deal of research which has explicitly addressed this problem. One interpretation, derived from handwriting experimentation (e.g., Merton, 1972; Wing, 1978), has been suggestive of movement duration and spatial relationships being context-consistent, whereas overall force specifications are free to vary, and this view has been supported by recent two-handed task data (Kelso, Southard & Goodman, 1979). Klapp (1977) has shown that muscle selection is parameterized at a relatively late stage in the specification process, as is

suggested by his statement that, "response programming, as assessed by reaction time, does not establish the commands for particular muscles" (p. 301).

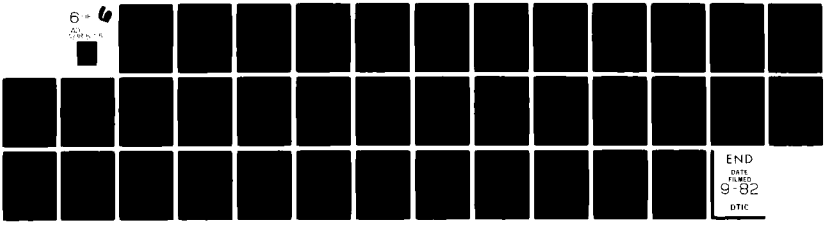
Mass Springs

A more accurate and attractive approach to control would be to develop a model based on the consistent finding that there is specification of final position. Supportive data have come from both behavioral research (e.g., Kelso, 1977; MacNeilage, 1970; Marteniuk & Roy, 1972) and from physiology. Early Russian work (Asatryan & Feldman, 1965; Feldman, 1966a, 1966b) in particular, is now being reinforced by a series of others which have focused on the dynamic characteristics of muscle. The original studies examined arm movements in response to sudden unresisted loadings or unloadings of external torques, and the conclusion was that the arm acted like an elastic system whose mechanical properties were not influenced by the external force changes. The model suggests that the nervous system preselects equilibrium points by choosing the parameter of zero or resting length of a muscle and if actual length does not equal this value, movement takes place. Although more complex than a simple spring, the basic argument is that the muscles act as a joint by virtue of their inherent non-linear vibratory or oscillatory characteristics so that regardless of initial location or external perturbations, the joint is capable of achieving the desired equilibrium point. Recent evidence has reinforced the contentions of this model. Bizzi's work (summarized in Bizzi, 1980) has revealed the primacy of an equilibrium point (between agonist and antagonist length-tention) specification. Bizzi and his associates found that learned arm and head target positions could be reproduced by normal and rhizotomized monkeys despite constant and acute load perturbations. Kelso (1977) found similar results in functionally deafferented human subjects.

These data, in addition to supporting an equilibrium hypothesis, effectively lay to rest some basic arguments by open-and closed-loop advocates and reveal some parameters and structures that cannot be involved in action specification. For example, details of the replication of target positions under deafferented conditions has long been an anathema to closed-loop arguments and open-loop theorists may have difficulty interpreting the achievement of final position under perturbed movement conditions. This finding is also contradictory (at least for undriectional movements) to Schmidt et al.'s (1979) remodeling of motor programs by the impulse-timing hypothesis. According to this hypothesis, and using the Bizzi paradigm, the perturbation of the moving arm would result in a shortened movement distance, since the force and duration specifications would have been met. Only if the precise length-tension ratio for agonist and antagonist muscles were made could a location be attained despite external torque application.

An important problem which arises from the Bizzi (1980) hypothesis is that the system would require immense storage capacity and computational capability if one specific equilibrium point is to be specified for one movement: from all the possible length-tension curves for the agonist and for the antagonist, one value, at the intersection point of these curves, needs to be specified. Accepting the point that the muscle does act like a non-linear spring, the problem of control of the spring is pivotal. Sakitt (Note 2) has suggested that an equivalent electrical means of overcoming this storage-computation overload would be a battery across a rheostat. The specification of the rheostat pointer would determine

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alpha motorneuron innervation (final position) and the battery would determine total innervation (overall muscle tension). Therefore, after determining joint angle on the rheostat equivalent, Sakitt suggests that any innervation will cause movement to the correct location. Does such an electrical circuit have a neural equivalent, or is some other mechanism involved in this supplementary and necessary parameterization?

The work of Houk (e.g., 1979) is relevant to these problems. He suggests that descending motor commands act to shift the threshold length of the motor servo (a negative feedback system involving stretch and unloading reflexes) and that they could act to modify muscle stiffness (the ratio of force change to length change) rather than to regulate just muscle length or provide load compensation. Therefore, in response to the mechanical parameterization question (i.e., whether it is length, force or some derivative thereof), Houk suggests that it is none individually "since a controlled change in threshold length acts to shift the entire relationship between length and force" (p. 112) which is then regulated by proprioceptive feedback. One might consider that the regulation of stiffness is not unlike regulating a rheostat pointer; the specification of resting length, by length-tension curves for example, is preset with other modifications (rate, acceleration and phasing) being made by altering stiffness and damping properties (Kelso et al., 1980).

One pivotal direction that many researchers of motor performance appear to be in the midst of taking is the depiction of movement control in terms of muscle dynamics and the coordination of groupings of muscles as single functional units. Recently gathered data, such as those of Bizzi, Cooke, Kelso et al., and Schmidt (all in Stelmach & Requin, 1980), when taken with those of Feldman (1966a, b), are reflecting the convergence

of conceptual, theoretical and empirically based positions. A complete understanding must be a future goal. Presently, there are a number of aspects which remain problematic. The data mentioned above, while giving support to contemporary theories of action, do not provide lucid explanations about multidirectional movements either in terms of control mechanisms or in terms of parameter specification (although it should be noted that alternatives to these hypotheses have yet to be consistently substantiated). Schmidt's recent (1980) suggestion that relative timing is a dominant aspect of action specification in reversed movements warrants expanded investigation and elaboration, and the exact nature of skeletomotor reflexes, after Houk's (1979) description, requires further examination also. Whether the parameterization of multilimbed movements is similar to that for single-limbed ones is unclear (compare, for example, Kelso et al., 1979 and Marteniuk & MacKenzie, 1980). The resolution of all these questions is certainly a challenge for the 1980's; the development of veridical explanations of control mechanisms, both theoretical and empirically determined, is crucial to the study of motor performance. Furthermore, the utility of such explanations may transcend those areas in which they will be derived; the Air Force and other institutions which rely very heavily on an excellence of motor skill performance should have particularly strong interest in the continuation of research in these areas. Again, practical significance will only be revealed when the true theoretical bases are determined, and the transition along the continuum between pure theoretical positions and methodology for the systems designer and instructor will only be accelerated by continued empirical evaluations.

# Automation

## Motor Skill Automation

As one progresses from an inexperienced to a skilled state, dramatic changes occur in motor performance. A widely held belief is that an inexperienced performer must spend considerable time and effort to regulate the movements demanded by a particular task; a process which requires active and conscious participation. In contrast, conscious involvement is uncharacteristic of an experienced individual's performance.

Despite these known characteristics, our knowledge about how motor skills are automated is surprisingly scant and certainly incomplete. In many ways psychologists know little more about the nature of automated motor skills than was stated or known in the 19th century (Stelmach & Larish, 1980). There is really no clear empirical support for automation, yet such a capability seems to be a necessity for an optimally designed motor control system. Perhaps this explains why so many are willing to intuitively accept the idea or assumption that motor skill automation is possible. Past research, however, has assessed automation in a cursory way, and has been confined to examining the motor act itself.

Through the years it has been assumed that the way to understand attention is by documenting the limitations of processing capacity. Consequently, numerous attempts have been made to define factors involved in limiting, controlling and directing attention (Kahneman, 1973; Keele, 1972; Moray, 1967; Norman, 1968). On the basis of this rationale, two distinct views of attention allocation have developed: one relating to capacity and the other to structure. A major problem that plagues the attention area is the inability of the capacity models (Kahneman, 1973; Norman & Bobrow, 1975) to provide a quantitative framework wherein the upper bounds of capacity can be determined. If a movement's attentional demand varies according to the nature of each task to be performed, it is difficult to

pinpoint the reasons for processing limitations when an explicit theoretical framework is nonexistent. Lacking a definable limit of attention, capacity models are at best global, fostering predictions too imprecise to allow for fair and adequate tests. In constrast, structural models (Keele, 1973; Posner & Snyder, 1975) have been subjected to rigorous evaluations because they are more concise, permitting the design of clear cut tests of their validity. However, capacity theorists contend that these tests have either utilized techniques insensitive to the small amounts of attention required by a process or that the difficulty of the tasks have failed to exceed the limits of the capacity system. Circular arguments such as these and the ability of each model to account for part or all of the other's research data is a major hindrance in revealing the nature and function of attention within the processing system.

Although the foregoing research and analyses may appear to be enlightening, they fail to provide definitive answers about the nature of performance automation. Important unsolved problems include the determination of the operational characteristics of this automatic state and the variables which influence the development of automation. Only after an understanding is gained with respect to these problems can we begin to make substantive statements about how motor skills become automated and what the antecedent conditions to motor skill automation are. The studies examining simultaneous motor performance were both equivocal and subject to numerous methodological criticisms (Bahrick, Noble & Fitts, 1954; Brown, 1962; Vroon, 1973). Further, the reaction time probe studies relate to automation only in the sense that they document which aspects of movement require attention (Ells, 1969; Posner & Keele, 1969; Salmoni, 1974).

Automatic Activation

In the section to follow, it is our intent to briefly develop a somewhat different perspective with regard to motor skill automation; namely,

the study of automatic sequences (for an expanded version, see Stelmach & Larish, 1980). Briefly, an automated sequence consists of memory associations which are activated in specific response configurations without active attention. Goal-directed movements are generally made in reference to some specific environmental context where the activating cue may be visual, auditory or kinesthetic. As a result, repetitive association of a specific environmental cue with a specific motor act, or a finite number of responses, is quite common. What may, in fact, explain automation is the development of an automatic sequence, such that the contextual situation automatically triggers the necessary action from the appropriate response class. Thus, a crucial aspect of automation involves the establishment of definite stimulus-response relationships involving the specific context for action where the automatic processes activate the retrieval of overlearned associations from well-established memory structures. The major point, then, is that we should no longer focus on just the motor act itself, but rather that we should emphasize the contiguity between context and action.

Associative and Automatic Learning

Recently, LaBerge (1975) and Shiffrin (1977) have developed models of perceptual and associative learning based on automatic activation. LaBerge views perceptual learning as a two-stage process: firstly, one learns to select among relevant and irrelevant stimulus features and secondly, the relevant features are organized into higher order cognitive units. Initially, both stages are subservient to attention control for the identification and coding of unfamiliar stimuli or events. Each experience with the novel event increases the strength of this coding, such that less attention is required for perceptual organization. Finally, with repeated exposures the necessity for attentional control to produce the codes is eliminated.

Schneider and Shiffrin (1977) and Shiffrin and Schneider (1977) extended LaBerge's ideas to include motor responses in automatic sequences. An automatic sequence consists of a systematic association of memory codes which have two properties: 1) the sequence of codes always becomes active in response to a particular input configuration, where the inputs may be externally or internally generated and include the general situational context, and 2) the sequence is activated automatically without the necessity of active attention by the subject (Schneider & Shiffrin, 1977). An example given by these authors is that of a red traffic light might initiate a braking response when someone is driving a car, yet a walking, halting or traffic scanning response when the same person is a pedestrian. Clearly, flight-related examples abound.

Perceptual learning, then, is analogous to the process of acquiring a new motor skill, where the learner must discriminate among relevant and irrelevant movements, and then organize the relevant movements into a patterned whole, the skill itself. As learning progresses conscious selection and organization is eliminated, and the initially independent movements are performed as a smoothly sequenced action. Associative learning involves the temporal-spatial congruity between an environmental event and the optimal motor response schema (Schmidt, 1976). We must re-emphasize that a mutual dependency between current context and action is being stressed. It can be said that automatic sequences consist of over-learned spatial-temporal associations between a set of environmental conditions and a motor schema appropriate to the current situation.

We are in agreement with Norman (Note 1) when he states,

"Conscious awareness of schemas is not necessary for performance.

The general idea is that well-learned plans need only be specified at the highest level. It is only with poorly learned acts or with novel rearrangements of well-learned components that conscious awareness of lower level components is required. When a plan is modified, however, there is a critical junction point at which the modification must occur, and if the required schema is not activated at that time, the regular, unmodified set will continue" (p. 24).

Examples of Automatic Sequences

We hope to illustrate the functional importance of automatic sequences by describing real-life behaviors that appear to be under automatic control. We believe that insight into automatic sequencing can be gained by observing non-random errors in performance. It will become apparent that motor slips most frequently occur when an habituated or routine motor act must be altered in the absence of conscious processing.

A number of excellent examples of automatic sequencing can be identified in flying behaviors. While a pilot's general intent may be to take-off or to fly in a particular pattern, certain behaviors can be considered specific and routine elements in the flying scheme. For many, these actions are even completed in a pre-specified, unaltered sequence each time one gets into the cockpit. In fact, these behaviors are probably habituated to the point that attention need not be given to their actual performance. These actions are certainly simple enough, but what happens to them when one must fly an unfamiliar plane? If the layout of the instrumentation panel is different, some very interesting, although more often dangerous, motor slips can occur.

One example can occur with the position of altimeter in the cockpit.

Some training simulators may have these devices in a certain position, whereas the actual plane may have it somewhere else. The pilot may, in the process of checking the altitude of the actual plane, "automatically" glance in the direction of the simulator's altimeter. Only after it is not found to be where it was originally thought to be, can an adjustment be made. Similar occurrences may occur in the reading of such instruments if their design and operations are not similar: "normal" reading methods may not give accurate information if two devices are designed to be read differently.

Another example can be derived from tower control of landings and takeoffs. Anyone who has been forced to use unfamiliar radar equipment having a radically different display or apparatus arrangement from their usual one can surely attest to the potential for motor slips. For someone who is a skilled flight controller the very necessary adjustments between context and action are indeed difficult and tedious. To accomplish this, a slow down in reading and response speed or a temporary halt and then readjustment to the new equipment is required.

What these examples illustrate is that there appears to be a close association among the intent to act, the context for action, and the motor schema. The intention defines the context for action, which in turn activates the motor schema best suited for achieving this intent. However variations in context will require alterations of the habituated actions in the motor schema. If conscious processing is not allocated to this end, motor performance errors will result. The point to be emphasized is that these performance errors are not random occurrences.

In all the behaviors described, a conditioned response was triggered by the current context, but because alterations in the context were not immediately realized, the necessary motor adjustments were not made. The automatic sequence is only incorrect relative to the changes in the environmental context. Hence, the normally associated actions were executed. The automatic responses were noticed only after attention and conscious processing were brought to bear on the situation.

Although the examples of automatic activation may be quite common and our arguments logical, we must go beyond mere intuition to develop an experimental framework in which questions about automation can be empirically assessed. The lack of a substantive knowledge base about automation and movement points out the difficulty in developing a suitable methodology. The study of automatic sequences, in conjunction with motor performance errors, has the potential to fill some of this void.

One characteristic of such a research endeavor is clear: automatic sequences must be examined in overlearned or highly practiced activities, a stipulation which poses a number of problems in an experimental setting. A possible solution is to take advantage of persons who are known to be highly skilled in tasks deemed suitable. Test pilots, flight instructors and experienced controllers, for example, would make excellent choices. Almost any skill role in which context and action are redundant and repetitive should be potentially useful.

Providing suitable experimental tasks can be devised, and we think they can (see Stelmach & Diggles, 1980) this approach should reveal important insights into the nature and structure of automated behaviors.

Furthermore, we should be able to ascertain the operational characteristics of the automatic state, along with the variables critical in developing automatic sequences, and hence motor skill automation. This relationship between automation and automatic sequencing is both functionally and theoretically useful, and in our view provides an exciting prospect for future research. Although this approach may not illuminate the entire picture about automation, we certainly believe it has the potential to advance the current state of the art.

## CONCLUDING REMARKS

We have attempted in this paper to offer our view of three topics possessing potential rewards for future investigations. However, if the Air Force research is to take advantage of these directions and make headway in their development, attention must be paid to the ramifications of studying a complex behaving system. To some extent this concern is reflected in a current research trend toward descriptive studies which focus on meaningful behavioral phenomena and utilize diverse dependent variables to capture some of the complexity that may escape the traditional measures of performance: accuracy and time to respond. These additional variables provide information conducive to developing a conceptual framework stressing how a behaving system controls and regulates coordinated motor acts and encourages an holistic view of motor behavior. A multidisciplinary approach to research would go far in achieving this view and can be arrived at only through a functional understanding of key concepts from a number of disciplines studying the biological and behavioral determinants of movement. Behavioral models in the past have changed in accordance with developments

in supporting disciplines and Air Force personnel are encouraged to take advantage of progress in each related discipline to advance their interests, be they theoretical or instructional.

Additionally, we recommend that a system as complex as the human nervous system be analyzed and conceptualized at different qualitative levels, a task accomplished only with a multidisciplinary approach. Marr and Poggio (1972) specified four important levels of understanding related to the object of scientific inquiry, equated here with the motor control system. At the first level investigation centers around the basic elements and components of the motor control system--such as neurons, muscle fibers, and motor units. The second level is that of mechanisms, combinations and composites of the basic components which act to perform specific functions and include sensory transducers, reflexes, synergies, etc. At the third level is the algorithm, describing the interaction and coordination of mechanisms. Sensorimotor integration, schema notions, cerebellar and cortical control of movement would all be representative of this level of inquiry. The remaining level is that of theory, the set of principles which govern the interactions of a collection of algorithms. There are logical and causal relations among the four levels of description and each will have its place in the eventual understanding of motor performance. However, individual disciplines often pursue research confined to one level with little consideration for the others. It should be obvious that the information available at a particular level can support the findings of another while generating new directions for further research at either level. Appreciation for the complexity and, we believe, understanding requires attention to these levels and the relations between them.

It is clear that the emerging picture of what a researcher of motor performance needs to know and to pursue is a bit staggering. The evolution of the human organism has developed a fantastically multi-layered system that changes or is mediated in so many ways that it almost defies analysis. Unless diverse approaches encompassing a variety of concepts and methods are sought, insights will not go beyond some narrow province of the area. Research focused on the description and analysis of motor performance requires increasingly specialized techniques and it will often proceed on a day-to-day basis with attention confined to the immediate demands of technical methodology and immediate theories. However, a broad, flexible, multidisciplinary framework which focuses on the conceptual understanding of motor performance is needed. Without it there is the danger that the future will produce fragmented, isolated, and competitive sub-disciplines where research ideas or situations become ends in themselves and where useful information will not be offered to the practitioner. If the future is to be bright, an attempt to cumulate and synthesize research findings in a broad perspective that stresses the biological and psychological determinants of coordinated acts must be made.

## FOOTNOTES

1. The nature of the system's 'language' can be included in a broader analogy: basic subsystem control levels and simple neurophysiological mechanisms may be regarded as a 'vocabulary' of actions from which are developed more specific and unique movements. This 'vocabulary' represents a practical working repertoire of acts (and not the total 'dictionary' of possible variations in muscle dynamics or innervation) which may be grouped into 'words' whose number is smaller than the possible combinations of 'letters' (Gelfand, Gurfinkel, Tsetlin, & Shik, 1971).

## Reference Notes

1. Norman, D.A. Slips of the Mind and a Theory of Action. Unpublished manuscript, 1979.

2. Sakitt, B. A Spring Model and equivalent neural network for arm posture control. Unpublished manuscript, 1979.

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# A New Perspective on Motor Skill Automation

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*MOTOR BEHAVIOR*

# A New Perspective on Motor Skill Automation

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For nearly two centuries the concepts of volition, automation, and attention have been of interest to psychologists (Bahrick & Shelley, 1958; Boder, 1933; Buchanan, 1812; James, 1890; Jastrow, 1891; Kantowitz, 1969; Posner & Keele, 1969; Sherrington, 1906; Woodworth, 1899). In the 19th century each of these three concepts held prominent positions in the introspective behavioral theories of that time. Buchanan (1812) viewed volition of voluntary behavior as a learned act encompassing "three principal and essential parts: an idea of some action to be performed; a desire of performing it; and ultimately the action itself" (p. 300). James (1890) expressed attention as "the taking possession by the mind in a clear and vivid form, one out of what seem several simultaneous possible objects or trains of thought . . . it implies withdrawal from some things in order to deal effectively with others" (p. 403). It also implies that attention is a necessary prerequisite for the performance of a voluntary motor act. However, it is also a well-known and experienced phenomenon that voluntary acts given sufficient practice appear to lose their reliance on attention; they proceed automatically. Jastrow (1891) expressed it this way, "We know that the shortening of mental processes brought about by practice is largely due to the power of doing two things at once, is an overlapping of mental processes; we know, too, that when processes become automatic they may accompany more deliberate and reasoned processes without interference . . . (p. 219).

As one progresses from an inexperienced to a skilled state, dramatic changes seem to occur in motor performance. Perhaps this is most evident in the transition

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of movement control from a conscious mode to an automatic mode (Adams, 1971; Fitts & Posner, 1967; Gentile, 1972; Robb, 1972). A widely held belief is that an inexperienced performer must spend considerable time and energy to perfect the movements demanded by a particular task, a process that requires the active and conscious participation by an individual. In contrast, conscious involvement is uncharacteristic of an experienced individual's performance. Rather, responding is so sophisticated that it is unnecessary to think about the actual performance of a movement pattern; consequently the movement proceeds automatically. An enormous research effort has been devoted to the behavioral phenomena associated with how one acquires a new or novel form of voluntary behavior (e.g., learning studies). However, much less emphasis and detail have been directed toward the phenomena associated with the operating characteristics of this automatic state. In many ways psychologists know little more about the nature of automated motor skills than was stated or known in the 19th century.

Although traditional notions about automation typically emphasize the attention reduction quality of performing the motor act itself, we would like to offer a slightly different view. Goal directed movements are generally made in relation to some specific environmental context, where the "signalling" cue may be visual, auditory, or even kinesthetic. As a result, repetitive association of a specific environmental cue with a specific motor act, or a finite number of responses, is quite common. What may, in fact, partially or totally explain automation is the development of an automatic sequence (Schneider & Shiffrin, 1977), such that the contextual situation automatically triggers the necessary action from the appropriate response class. Thus, a crucial aspect of automation involves the establishment of definite stimulus-response relationships where the specific context for action is an important factor. The major point, then, is that we should no longer focus on just the motor act itself, but rather emphasis should be placed on the contiguity between context and action.

To begin this article, the concept of attention is introduced and the major theoretical positions concerning the nature of attention allocation are presented. The discussion then turns to the study of motor skills and a review of the research findings concerning attention, automation, and movement. After concluding that our knowledge about motor skill automation has failed to answer some important questions, we introduce what we consider to be a more reasonable avenue of study: automatic sequencing. The theoretical position is put forward, substantiated with empirical support, and a number of everyday examples are used to illustrate the utility of our ideas. Finally, we end with suggestions for beginning empirical observations of automatic sequences.

## Concepts of Attention

It has been argued since the dawn of modern psychology that man is limited in the amount of information that can be processed at any given time (Buchanan, 1812; James, 1890; Jastrow, 1891). Such an assertion has been the foundation upon which psychological research has sought to determine the nature and quantitative bounds of attention. By examining the limitations of processing capacity, an attempt has been made to define factors involved in limiting, controlling, and directing attention. On the basis of the above rationale, two distinct views of attention allocation have developed: capacity and structural.

Capacity models (Kahneman, 1973; Moray, 1967; Norman & Bobrow, 1975) are based on a processing system containing a limited capacity or pool of attention. Also, all mental processes are assumed to require attention, and processing capacity can be flexibly allocated to any number of input channels or processing operations. When the demands of two or more simultaneous operations exceed the system's capacity, decrements in performance ensue. This interference, defined as a reduction in the efficiency of transmitting information (Kahneman, 1973; Kerr, 1973), is nonspecific and depends solely on the summated demands that simultaneous processing operations levy on the limited capacity system.

In contrast, structural models (Broadbent, 1958; Deutsch & Deutsch, 1963; Keele, 1973; Norman, 1968; Posner & Snyder, 1975b) have a more rigid view of attention allocation. These models maintain that early processing stages (i.e., detection and recognition) can operate without attention, whereas later processing stages (i.e., decision, response selection, rehearsal) cannot. In addition, only one operation at a time can demand attention, regardless of their summated demands. Finally, it is possible for a process that does not require attention to operate while attention is allocated to another process.

The current empirical evidence, however, is not as clear and concise as the differences between these two models appear to be. The difficulty lies in experimentally distinguishing between the two models. Since both models argue that different operations will demand varying degrees of processing capacity and that competition between processes causes interference, there appears to be no way to discriminate between the predictions of these two models (Kerr, 1973). As a result, experiments have been designed that test only one model, rather than directly testing one against the other.

A major problem underlying this dilemma is the inability of the capacity models to provide a quantitative framework wherein the upper bounds of capacity can be determined. If attentional demands vary according to the nature of each task to be performed, it is difficult to pinpoint the reasons for processing limitations when an explicit theoretical framework is nonexistent. Lacking a definable limit of attention, capacity models are at best global, fostering predictions too imprecise to allow for a fair and adequate test.

In contrast, structural models have been subjected to rigorous tests because they are more concise, permitting the design of clear-cut experiments to test their validity. However, capacity theorists contend that these tests have either utilized techniques insensitive to the small amounts of attention required by a process or that the difficulty of the tasks failed to exceed the limits of the capacity system. Circular arguments such as these and the ability of each model to account for part or all of the other's research data are a major hindrance in revealing the nature and function of attention within the processing system.

Another drawback of each model is that both were developed primarily to explain limitations in human information processing (i.e., how do we select information to be processed?), and then, as a secondary consideration to explain the nature of the processing system (i.e., what processes are involved). An alternative and perhaps more logical approach, however, would be to define initially the characteristics of the mental operations within the processing system and subsequently determine the operations which do and do not require attention (Massaro, 1975; Posner, Nissen, & Ogden, Note 2). Once such a framework is adopted, we may better understand limitations in human information processing.

Recent developments in the study of attention favor the latter approach (LaBerge, 1975; Posner & Snyder, 1975b; Shiffrin & Schneider, 1977), where emphasis is placed on the distinction between automatic processing and conscious processing. Conscious processing requires active attention, is volitional, and is under direct control of the individual. In contrast, automatic processes occur unintentionally, without an individual's conscious awareness, and in parallel with processes requiring attention. Studying attention from this perspective allows one to develop a comprehensive framework that accommodates both the structural and capacity models.

At the same time it affords the specificity necessary for defining the sequence of mental operations and determining where in the sequence attention promotes optimal processing and responding. For the purposes of the present review, further discussion is confined to the issue of automatic processing and a more detailed account of automatic processing is included in a later section.

## Attention, Automation, and Movement

The concept of automation has played a prominent role in psychological theory and in application to practical skills, especially with respect to motor skills. The phenomenon of automation is well known in everyday life.

> . . . responses acquired, as Buchanan said, "at the expense of much labor," gradually lose their laborious quality. They become automatic, occur apart from any direct attention on the performer's part and are commonly called "involuntary." A closely related observation is that the act of paying attention to such performances or describing the steps as they occur tends to destroy the automaticity of such behavior. In addition, such behavior seems somehow freed of its usual control by motivation and feedback. Such responses seem to happen "on their own," independently of their consequences and without an easily demonstrable, motivational base. It seems to us that the importance of this process of automatizing behavior is that it allows certain aspects of behavior to proceed while the individual devotes his attention to more demanding enterprises (Kimble & Perlmutter, 1970, p. 375).

Jastrow, as early as 1891, expressed these same sentiments. Are these intuitive introspections correct? If so, how do these changes take place? What is the function of attention in the control of movements?

**Attention demands of simultaneous performance.** Initial investigations of movement automation focused on whether two gross overt acts could be performed simultaneously. Binet (1894) and Bliss (1892) maintained that voluntary movements can be automated to the point where attention is dispensable. In fact, Bliss reported that responding was disrupted when automated tapping movements were attended to. Bahrick, Noble, and Fitts (1954) demonstrated that when a visual-motor task was repetitive and highly practiced, performance on a mental arithmetic task actually improved. Since identical results were not obtained when the visual-motor task was random or in early stages of learning, Bahrick et al. concluded that a reduction in the attention requirements of the visual-motor task took place, which allowed additional processing capacity to be redirected to the mental arithmetic task. Bahrick and Shelley (1958) also reported evidence supporting this attention reduction hypothesis. They found decreases in reaction time on a secondary task as a primary motor task became redundant and well learned. Brown (1962) found that performance of an auditory task had no "measurable adverse

effect upon driving." Additionally, Vroon (1973) provided support for the automation of a repetitive tapping task.

Despite these findings, there are a number of investigations which militate against the automaticity of motor skills. Loeb (1884) and Welch (1898) showed that variability in constant hand pressure increased with simultaneous performance of mental activities. Similarly, Boder (1935) in reexamining Bliss's findings, found increased variability in tapping when subjects were asked to perform a concurrent secondary task. Finally, Brown and Poulton (1961) demonstrated impaired driving ability in complex driving situations when a simultaneous task was performed.

**Attention demands on movement execution.** It is clear that the above attempts to use the secondary task technique as a means of associating automation with a reduction in conscious involvement have resulted in equivocal findings. Part of the reason is that the secondary tasks used have been restrictive in their applicability, both because of methodological problems and because of problems in making valid inferences from their results (Salmoni, 1974). Attempting to alleviate some of these problems, Posner and Keele (1969) used an alternative secondary task technique, called the reaction time probe. From the use of this technique, a second focus of automation research developed whose primary concern was to measure the demands of component processes within a particular task. Is attention necessary for response initiation and movement termination? Does feedback monitoring and movement correction require attention? Does the prediction of a future movement require processing capacity? Does the precision requirement of a movement task affect its attention demands?

The basic tasks require a subject to execute a primary movement, and before, during, or after the execution an auditory stimulus (probe) is presented. Subjects are instructed to continue the primary task and also to respond to the tone as quickly as possible by pressing or releasing a reaction key. Probe reaction time for each movement is compared to a control reaction time condition where subjects' only concern is to respond to the probe (no movement). Reaction time to the probe during a specific movement phase is used as the measure of attention for that particular movement phase. The greater the demand of the movement phase, the slower the processing of the probe and, thus, the slower the reaction time. On the other hand, if attention is unnecessary for a movement phase, control probe reaction times and movement phase probe reaction times should not differ.

In a precursor to probe experiments, Moore (1904) reported that an arithmetic task performed while making an arm movement increased both reaction time to begin the movement and movement time. Moore interpreted these results as evidence for the apparent attention demands of both movement preparation and movement execution. Using the probe technique Ells (1969), Posner and Keele (1969), and Salmoni (Note 5) verified the attention demands of movement initiation.

In Posner and Keele's (1969) initial experiment, subjects moved a pointer to a fixed target position that varied in size (small or large); on two-thirds of the trials an auditory probe was presented at varied times throughout the movement. The results showed probe reaction time to be elevated early (movement initiation) and late (movement termination) in the movement. Results also found greater attention demands throughout the entire movement as precision increased (i.e., small target).

In a second experiment the processing capacity of visually guided and blind movements were contrasted. Visually guided movements were made to a visually

marked target or to a remembered visual location, while blind movements were made to either a mechanical stop or to a remembered position of the stop. The results replicated the "U" shaped probe reaction time function of their initial experiment. Moreover, reaction times were slower when the terminal location had to be retained. Such a result was probably found because processing capacity was necessary to maintain the location's representation in memory. The most intriguing result, however, came from the comparison of probe reaction times of blind movements with no movement controls. Excluding movement initiation and termination, the differences between movement and control reaction times were nonsignificant, suggesting that the actual movement phase does not always require attention.

Using the same probe technique, Ells (1969) varied not only movement precision but also directional uncertainty. In most respects Ells replicated the Posner and Keele results. In an initial experiment, directional uncertainty increased the attention needed to prepare for movement execution, and the attention needed for the completion of a simple movement was a function of movement precision. Ells, however, was unable to replicate the "U" shaped probe reaction time function found by Posner and Keele. Rather than a "U" shaped function, Ells's data revealed an "L" shaped function. Probe reaction times were elevated during movement initiation, but not at movement termination. The former finding is consistent with Posner and Keele's results, whereas the latter finding is inconsistent.

Ells reasoned that the discrepant results were due to greater overshooting of the target and the subsequent need for movement corrections by Posner and Keele's subjects. In a second experiment, Ells confirmed his suspicions and demonstrated the apparent attention demands of movement correction. Credence is added to this interpretation when one compares the movement times in these two studies. Average movement times in Ells's study were between 100 and 400 msec, 200 msec faster than in the Posner and Keele study. The minimum time necessary to process visual feedback from a movement has been established at approximately 190–200 msec (Keele & Posner, 1968). In general, movement corrections for Ells's subjects would have been difficult, while highly probable for Posner and Keele's subjects. If this explanation is correct, increased reaction times near the end of the movement are a function of the attention demands of movement correction.

Despite Ells's contention, Salmoni (Note 3), argued that at least part of the difference between the "U" and "L" shape functions was the result of subject expectancies for the probe, rather than movement corrections. Recall that Posner and Keele's subjects received the probe on two-thirds of their trials. In contrast, Ells's subjects were presented the probe on every trial. Thus, as the probability of probe occurrence increased at the end of the movement, subjects' expectancy for the probe could have been heightened, decreasing probe reaction time. Contrasting each condition in a single experiment, Salmoni replicated both the "U" and "L" functions. Therefore, one is forced to conclude that Ells's results were primarily a function of probe frequency and not movement corrections.

Returning to the issue of movement corrections, a pertinent question to be asked is what is it about a correction that requires attention? Is it the monitoring of feedback channels, initiation of the corrective movement, or both? Based on studies previously discussed, there is evidence suggesting that it is the initiation of the movement. Further substantiation is provided by studies showing input or feedback monitoring to be nonattentive (Fitts & Peterson, 1964; Salmoni, 1975; Wickens, 1976). These results are only suggestive, however, because the information moni-

tored in these latter studies is unlike that used in the control of movement (Klein, 1976). An adequate experiment to distinguish between initiation and monitoring during a movement has yet to be carried out.

Often during movement execution, individuals must process information which will affect the future course of their actions. Kerr (1975) addressed this issue with regard to the attention demands associated with such processing. Subjects were required to move a stylus through a semicircular track under two conditions. In the first group, subjects were told prior to movement execution which of two paths at the end of the track to move into. In the second group, subjects were informed of the correct path following movement initiation. Similar to the probe technique, subjects who began the movement without knowing the terminal path were informed of the correct path at various stages into the movement. In this group movement times and attention demands were the greatest. Kerr suggested that this finding was the result of subjects focusing attention on an expected signal. In support of this interpretation, Posner and Snyder (1975a) and Laberge, Van Gelder, and Yellot (1970) have shown that expectations do create an attentional set which inhibits other signals from accessing attention.

Another contributing factor to movement automation is the ability to process relevant stimulus information at a nonconscious level. It is well documented in the visual and auditory modalities (see Massaro, 1975) that the initial stages of processing, detection and recognition, can function without attention. Recent evidence in the kinesthetic modality also supports this view. Salmoni (1975) devised a technique which used hand cranking as the primary task and kinesthetic recognition as a secondary task. Subjects were required to crank a handle at a constant speed, while simultaneously monitoring finger stimulation on the left hand. When a predetermined finger was stimulated, subjects released a foot pedal. Foot pedal reaction time was used as one measure of attention demands, and cranking variability was a second. Reaction times on the recognition task were no different between simultaneous and singular conditions, indicating the nonattentive nature of recognition in this instance. Hand cranking variability remained unaffected, providing additional support for the above contention. One shortcoming, however, was that the information monitored may be unlike that involved in movement control (Klein, 1976), that is, subjects were not required to use the monitored information to alter or correct the hand cranking task.

Using a tracking task, Wickens (1976) demonstrated the attentive nature of response processes. Wickens selected tasks that, he argued, required distinct processing demands: an auditory signal detection task which involved input processes, and thus no attention; a force application task which involved output processes, and thus attention; and a tracking task which involved both input and output processes, and also attention. All possible pairwise combinations of these tasks were administered to subjects. The results revealed that the greatest difficulty in time-sharing occurred between the tracking and force application task while time-sharing was possible in the detection-tracking and the detection-force application conditions.

Based on the studies cited thus far, one may conclude that response initiation and movement corrections are attention demanding since they interfere with other tasks performed concurrently. Indirect evidence indicates that initiation of corrective movements is attention demanding, while feedback monitoring is not. Also, for a relatively unpracticed movement, information processing about the movement

itself interferes with its execution, whereas the tendency to exhibit automation occurs when this processing is eliminated (e.g., blind movements). Finally, input monitoring of secondary tasks fails to disrupt primary task performance and is therefore thought to operate independently of attention.

## Automatic Sequencing

Although the foregoing analyses may be enlightening, they fail to provide definitive answers about the nature of automation. Important questions remaining are: (1) What are the operational characteristics of this automatic state? and (2) What variables influence the development of automation? Only after an understanding is gained with respect to these problems can we begin to make substantive statements about how motor skills become automated and what the antecedent conditions to motor skill automation are.

As we mentioned, the studies examining simultaneous motor performance were both equivocal and subject to numerous methodological criticisms. Further, the reaction time probe studies relate to automation only in the sense that they document which aspects of movement require attention. In other words, they really do not provide insight into the nature of automation and, even if such an implication can be made, it is at best something of a default argument.

In this section, it is our intent to develop a somewhat different perspective with regard to motor skill automation, namely, the study of automatic sequences. Briefly, an automated sequence consists of memory associations that are activated in specific response configurations without active attention. To begin, background information concerning automatic information processing is presented. Afterwards, the notion of automatic sequencing is further developed, including the presentation of an associative learning model developed by LaBerge (1975). To reinforce these ideas, everyday examples, suggestive of automatic sequencing, are described. Finally, an attempt is made to put these ideas within an experimental framework.

An underlying feature of this section will be the distinction between conscious and automatic information processing. Several recent theories of long-term memory retrieval (Collins & Loftus, 1975; Keele, 1973; LaBerge, 1975; Posner & Snyder 1975b; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977) distinguish between conscious and automatic operations. Conscious processing is intentional, subject to cognitive manipulations, and under direct control of attention, whereas automatic processing can be unintentional, strategy independent, and free of attentional restrictions. A general consensus of the above positions is that automatic processes activate the retrieval of "overlearned" associations from well-established memory structures. In contrast, conscious processing, which is dependent on the limited capacity central processor, functions to retrieve less well-learned information and to establish the associations necessary for the eventual control by automatic processes.

Perhaps one of the clearest demonstrations of automatic processing is a phenomenon known as the Stroop color-word effect (Keele, 1972). In the basic task one is asked to identify the color of the print in which a word is written. Such a task can be performed rapidly and accurately if, for example, the letters spell a number. The task is considerably more difficult, however, if the word itself represents an alternative, conflicting color. For example, the word "red" may be written in green

ink. In marked contrast to the number example, this latter situation is a difficult one indeed. In a speeded paradigm (identify the colored print as quickly as possible), it is much more difficult and takes longer to read the color when the letters indicate color names than when they spell numbers. In fact, it is difficult to consciously suppress the word name and respond with ink color. This finding suggests that the word name has direct access to its memorial representation independent of attention, and the Stroop phenomenon has recently been recognized as an important indicant of automatic processing (Norman, 1976).

**Automatic activation.** One automatic process that has received extensive scrutiny is referred to as automatic activation. In theory, a stimulus automatically activates its stored representation (name code) in long-term memory. Furthermore, this activation spreads to memory codes that share common features, while memory codes that share fewer features are less affected. What has been proposed is a memory code network or hierarchy where integrally related codes concentrate together and dissimilar or unassociated codes are represented in the peripheral boundaries of the hierarchy (Fischler, 1977; Warren, 1977).

An additional property of such a system is that the network activation can be maintained for a short period of time following stimulus presentation. If another stimulus within the hierarchy enters the system during this period its activation level will be higher than it would normally be had it been preceded by an unrelated stimulus, and the result will be a facilitation in its processing time (Posner & Snyder, 1975b). The presentation of two stimuli in this manner has been referred to as priming.

***Evidence for activation through priming.*** To date, the majority of evidence for the facilitory effects of priming has come from semantic research. Eichelman (1970), using a same-different task, found reaction times to be faster following stimulus repetition (when a letter was identical in form and name to the succeeding one) than response repetition (the letter had the same name but a different form from the preceding one). Eichelman suggested this might be due to the savings in time required to "read-in" the stimulus when it is physically identical to the preceding one. In other words, stimulus organization might be easier when successive letters are visually identical.

LaBerge, Van Gelder, and Yellot (1970) combined a cued reaction time task with varied probability contingencies of the prime, and they also found faster reaction times for stimulus repetitions. Based on results from a same-different task involving physical (i.e., AA) and name (i.e., Aa) matches, Beller (1971) postulated two separate effects of priming. The data revealed facilitory effects in matching for both primed physical and name matches. Beller attributed the effects of physical matches to stimulus encoding, where subjects used advance information to preconstruct a partial representation of the expected stimulus. Since less of the stimulus needed to be processed to complete its memory representation, matching on the basis of a partially preconstructed representation was faster. As for name matches, they necessarily rely upon information stored in long-term memory, and Beller argued that advance information activated the stimulus' representation in long-term memory and placed it in short-term memory. If one assumes that access of long-term memory is made through short-term memory, priming reduces the number of steps involved in recognition and subsequent recognition time.

Kirby (1976) manipulated subjective expectancies of repetitions and alterations. He found evidence that decreased reaction times to stimulus repetitions with interstimulus intervals less than one second were a function of automatic activation. The time course of the spread of activation was further studied by Warren (1977) using naming latency as the measure of activation in a variable-duration priming paradigm. The results revealed a facilitation in naming the second of two words when they shared the same name (name identity) or an associative relationship. The increase in facilitation was linear up to about 150 msec and began to asymptote between 150 and 225 msec, further supporting Kirby (1976) and Posner and Snyder (1975b).

In a lexical decision task, Fischler and Goodman (1978) also examined the time course of activation in semantic memory. In this instance, priming effects were found to begin even after a 40 msec stimulus-onset-asynchrony. The results of these studies substantiate Posner and Snyder's (1975b) claim that activation is closely time-locked to the input signal and is of short duration.

Ells and Gotts (1977) showed that responses to symbol repetitions were faster than responses to nonrepetitions, supporting the hypothesis that cognitive operations responsible for forming an internal stimulus representation and matching it with a memory array are performed more efficiently when the same information is processed in succession. Fischler (1977), Neely (1977), and Schvaneveldt and Meyer (1973) further extended the notions of facilitation and inhibition in lexical decision tasks by showing that a category-name prime facilitates the subsequent processing of good and poor exemplars. When comparing priming effects on good and poor exemplars, Massaro, Jones, Lipscomb, and Sholz (1978) found that the facilitating effect of a category prime on perceptual processing is inversely related to the quality of the stimulus information available. On the basis of these studies, then, there seems to be substantial empirical support for the existence of automatic activation.

**Perceptual and associative learning.** Recently, LaBerge (1975) and Shiffrin and Schneider (1977) have developed models of perceptual and associative learning based on automatic activation. LaBerge views perceptual learning as a two stage process. First, one learns to select among relevant and irrelevant stimulus features. Second, the relevant features are organized into higher order cognitive units. Initially both stages are subservient to attentional control for the identification and coding of unfamiliar stimuli or events. Each experience with the novel event increases the strength of this coding, such that less attention is required for perceptual organization. Finally, with repeated exposures the necessity for attentional control to produce the codes is eliminated.

Associative learning is conceptualized in three stages: (1) episodic coding, (2) direct linkage with attention, and (3) direct linkage without attention. Episodic coding involves naming the perceptual code developed in perceptual learning. The name and code enter episodic memory where temporal-spatial congruity is the basis for name-recall. That is, the time-and-space episode triggers the recall of the associated name (LaBerge, 1975). As the association frequency increases a direct link between the name and code is established. At first, the process still requires attention, but eventually a direct link is established, where stimulus presentation evokes the name without contributions from attention.

Schneider and Shiffrin (1977) and Shiffrin and Schneider (1977) extended

LaBerge's ideas to include motor responses in automatic sequences. An automatic sequence consists of a systematic association of memory codes which have two properties: (1) the sequence of codes always becomes active in response to a particular input configuration, where the inputs may be externally or internally generated and include the general situational context, and (2) *the sequence is activated* automatically without necessity of active attention by the subject. The specific codes within a given hierarchy that will be included in the sequence can also vary, depending on the situational context. An example given by Schneider and Shiffrin is: a red traffic light might initiate a braking response when someone is driving a car, yet a walking, halting, or traffic scanning response when the same person is a pedestrian.

In our view, perceptual learning is analogous to the process of acquiring a new motor skill, where the learner must discriminate among relevant and irrelevant movements, and then organize the relevant movements into a patterned whole, the skill itself. As learning progresses, conscious selection and organization is eliminated, and the initially independent movements are performed as a smoothly sequenced action. Associative learning involves the temporal-spatial congruity between an environmental event and the optimal motor response schema (Schmidt, 1976).

We must re-emphasize that a mutual dependency between current context and action is being stressed. It can be said that automatic sequences consist of overlearned spatial-temporal associations between a set of environmental conditions and a motor schema appropriate to the current situation. Although the primary plan or intent may be consciously selected, if other subordinate specifications are habituated components in the schema they will be activated and executed automatically. In fact, once these automatic sequences are fully developed it is difficult to suppress or modify them without conscious intervention.

For some time now we have been interested in the interaction between context and action, along with their mutual roles in automatic sequencing. As a consequence, we have been forced to evaluate the types of behavioral settings in which automatic sequences exist and in which they could be experimentally studied. A rather obvious prerequisite is the use of behaviors that are context conditioned and highly overlearned.

One other major concern has been the selection of an appropriate dependent measure. After careful deliberation, however, we have become convinced that the operating characteristics of the automatic sequence can be best illuminated via motor performance errors. Errors have been successfully used as indicators of motor performance in the past (Restle, 1972; Restle & Brown, 1970; Restle & Burnside, 1972; Rabbitt, 1966; Rabbitt & Vyas, 1970; Rabbitt, Vyas, & Fearnley, 1975), yet they have failed to achieve the same degree of popularity as reaction time. Perhaps the reason for this situation is that in reaction time research, one typically wants to minimize errors in performance. In the view of Rabbitt and Restle, however, the intent is to induce or create errors; based on the conditions responsible for an error and the type of error committed, inferences about the structure of the behaviors being examined can be made.

More recently, Norman (Note 1) is constructing a theory of action that relies heavily on the analysis of motor performance errors. Although Norman's interests in taxonomy errors are much broader in scope than our ideas, or even Rabbitt's or Restle's ideas, a common framework exists within which the primary theoretical

assumption is that errors in performance are nonrandom events. That is, errors are a function of some antecedent events and the specific nature of such errors can be a valuable resource in the description of the motor control system.

Before we discuss any experimental treatment of these problems, we would first like to illustrate how automatic sequences have a pervasive influence over many everyday routine behaviors. For the most part the examples presented in the next section will reveal that motor performance errors most frequently occur when a habituated motor act must be altered in the absence of conscious processing.

**Examples of automatic sequences.** In this section we hope to illustrate the functional importance of automatic sequences by describing a few real-life behaviors that appear to be under automatic control. In the strictest sense, reflexive behavior is the purest form of automatic sequencing. Such behaviors, however, are not included in our categorization since reflexes usually do not involve intention and planning.

A number of excellent examples of automatic sequencing can be identified in car driving behaviors. While the general intent is usually to drive to a particular location, behaviors such as unlocking the door, turning on the ignition, fastening the seat belt, releasing the parking brake, and shifting can be considered specific and routine elements in the driving scheme. For many, these actions are even completed in a prespecified, unaltered sequence each time one gets into the car. In fact, these behaviors are probably habituated to the point that attention need not be given to their actual performance. These actions are certainly simple enough, but what happens to them when one must drive an unfamiliar car? If the inside layout of the car is different, some interesting motor performance errors can occur.

The first example occurs when an individual switches from a car with the shifting lever on the floor to one in which the lever is situated on the steering column. When it is time to shift, one often "automatically" reaches down toward the floor searching for the gear shift. Only after it is not found, does one realize it is positioned in another location, and now conscious processing is required to (1) define the new environmental constraints and (2) reorganize the motor act to conform to the new context. A similar example involves the placement of the parking brake. In some cars it is off to the left below the steering wheel, and in others it is along the right side of the driver's seat. Here again, when the car is unfamiliar, a common action is to reach to the "normal" location of the parking brake only to find it is not there. In other words, once the intent to engage or release the parking brake has been specified, experienced drivers do not consciously organize the desired actions to achieve these goals (e.g., This is what I must do and this is how I must do it). Consequently, when attention is focused elsewhere variations in the context go unnoticed and the habituated action is executed in its learned form irrespective of the adjustments demanded by the environment, thereby creating a motor performance error.

One final example comes from typewriting. Anyone who has been forced to type with an unfamiliar typewriter having a different keyboard arrangement from their usual one (usually involving special keys such as the margin release and backspace) can surely attest to these performance errors. That is, one continually reaches to the area that has been habitually associated with one of these keys in the past. For someone who is a skilled typist the necessary adjustments between context and action are indeed difficult and tedious. To accomplish this it usually requires slowing down typing speed or stopping altogether and then locating the new position of the key

What these examples illustrate is there appears to be a close association among the intent to act, the context for action, and the appropriate motor schema. The intention defines the context for action, which in turn activates the motor schema best suited for achieving this intent. Returning to the car driving example, the intent is to go home and the context is determined by how one will get home. The motor schema for car driving is the result of the current context.

In our examples the general intent remains invariant; however, variations in context required alterations of the habituated actions in the motor schema. Since conscious processing is necessary to recognize these changes, but is typically uncharacteristic of habituated actions, the routine learned actions were elicited rather than the newer, modified ones. The point to be emphasized is that these performance errors are *not* random occurrences (Norman, Note 1). They do not simply happen by chance. In all the behaviors described, a *conditioned response* was triggered by the current context, but because alterations in the context were not immediately realized the necessary motor adjustments were not made. Keep in mind, however, the automatic sequence is only incorrect relative to the changes in the environmental context and the normally associated actions are identified as inappropriate in this instance only after attention and conscious processing are brought to bear on the situation.

Another common feature of these performance errors is that they occur most frequently when attention is diverted to some other activity. Furthermore it is not unusual for these errors to occur a number of times before the automatic sequence is altered, and again the reorganization process must be completed at a conscious level with attention. Anyone who has experienced these or similar circumstances can surely attest to the difficulty of suppressing and the laborious nature of modifying the automatic sequence.

**Empirical assessment of automatic sequences.** Although the examples in the previous section may be quite common and our arguments logical, we must go beyond mere intuition to develop an experimental framework in which questions about automation can be empirically assessed. The lack of a substantive knowledge base about automation and movement points out the difficulty in developing a suitable methodology. The study of automatic sequences, in conjunction with motor performance errors, has the potential to fill some of this void.

One characteristic of such a research endeavor is clear: automatic sequences must be examined in overlearned or highly practiced activities, a stipulation which poses a number of problems in an experimental setting. A possible solution is to take advantage of persons who are known to be highly skilled in tasks deemed suitable. Professional typists, concert pianists, and skilled athletes, for example, would make excellent choices. Most any activity in which context and action are redundant and repetitive should be potentially useful. Further, the study of motor performance errors has much to be recommended. In skilled typists, pianists, or athletes automatic sequences would already be developed and it would only be necessary to devise methods of inducing errors. In this latter regard, dual task methodology (Kantowitz & Knight, 1978) is one possible alternative.

A necessary precursor to any experimentation would be the identification of a number of automatic sequences in a given task. Once this is accomplished a typical experiment can be arranged similar to the circumstances that occurred in the real life examples. More specifically, the automatic sequence is initiated, conscious

tions in the situational context are introduced. Not only can one examine and classify errors in performance, but the characteristics of the secondary task itself can be varied and the effects on performance observed. For instance, the secondary task can be motor or cognitive in nature and the difficulty level can be manipulated. Another dependent measure possible is the length of time to alter and reorganize a new sequence into the automatic mode. Perhaps even an experimental task, such as step tracking, can be incorporated in a way to study the development of automatic sequencing.

Experiments within a reaction time paradigm might also be devised. One possibility is to introduce alternative actions at critical points in the movement sequence (see Restle, 1972). If two such choices are used, the first can be designated as the primary one, and practice sessions would be given so that this action becomes a habituated response in a sequence. After the habituated response is sufficiently strengthened, a second experimental phase can be initiated where an alternative choice is introduced in a probabilistic manner. That is, the primary (habituated) action and the second alternative would have an equal chance of being inserted into the context-action sequence. Again, this situation might include the dual task methodology. Both errors and time to initiate the required action could be the dependent measures. Expected patterns of results would be more frequent errors when the unlearned element is inserted into the sequence and higher reaction times to initiate the unlearned action.

## Concluding Remarks

At present, our knowledge about how motor skills are automated is surprisingly scant and certainly incomplete. In fact, there is really no clear empirical support for automation, yet such a capability seems to be a necessity for an optimally designed motor control system. Perhaps this accounts for why so many are willing to intuitively accept the idea or assumption that motor skill automation is possible. Past research, however, has assessed automation in a cursory way and has been confined to examining the motor act itself. From the current perspective, a more important consideration is the relationship between the environmental context and action. It has been specifically proposed that the contiguity and specificity which develops between context and action is a focal point for automation. Although this approach may not illuminate the entire picture about automation, and we are not advocating that it will, we certainly believe it has the potential to advance the state of the art farther than it currently has progressed.

Some might argue that the ideas forwarded in the present paper are not new, that instead we use different terminology to describe familiar phenomena. One could alternatively view an automatic sequence as a motor program. To a certain degree this observation is correct. The point to remember, however, is that motor skill automation is not usually conceptualized in terms of automatic sequencing. Providing suitable experimental tasks can be devised, this approach should reveal important insights into the nature and structure of automated behavior. Furthermore, we should be able to ascertain the operational characteristics of the automatic state, along with the variables critical in developing automatic sequences, and hence motor skill automation. This relationship between automation and automatic sequencing is both functionally and theoretically useful and, in our view, provides an [illegible] for future research

## Reference Notes


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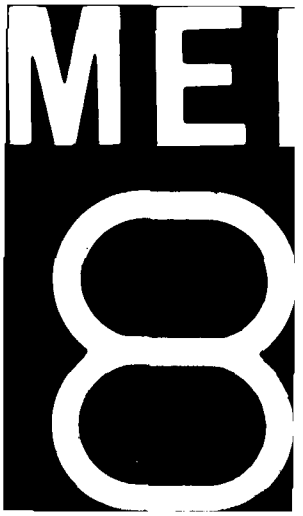
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