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**LA THÈSE A ÉTÉ
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THE EFFECT OF PERCEPTUAL OR
MOTOR PRACTICE
ON
REACTION TIME
AND MOVEMENT TIME

by

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CHAPTER I

INTRODUCTION

In the past, reaction time has undergone numerous experiments and reviews. The reaction time interval has typically been thought to contain only cognitive processes relative to the experimental task, with physiological lag and motor processes being kept to a minimum. Consequently, a great deal of interest has been generated by the manipulation of various variables to affect the reaction time interval. Based on the result of these manipulations, inferences could be drawn regarding the underlying cognitive processes. This provides a means by which hypothetical cognitive processes could be substantiated by the experimental manipulation of variables affecting those processes.

Rationale

Recently, several authors, notably Sternberg (1969) (see page 45) and Theios (1975) (see page 59) have proposed multistage models describing the processes that occur during the reaction time interval. These processes were related to an experimental task involving the recognition of a stimulus and the performance of a corresponding motor response. The cognitive processes could be divided into three areas relative to the experimental task: recognition of a stimulus, selection of the response and motor programming.

With the above categorization of the cognitive processes it is possible to consider variables that differentially affect the first or second of the two process categories, but not the third. An increase or decrease in the efficiency of the processes would be reflected in a decrease or increase in the reaction time.

Statement of the Problem

Specific practice was selected as a variable that might differentially affect different cognitive processes occurring during the reaction time interval. The experimental task was divided into two components: the stimulus recognition phase and the motor response phase. Specific practice of the first phase involved recognition of the stimulus and its association with a specific response key. This practice was hypothesized to involve stimulus recognition and response selection processes. Practice of the second phase involved the repetition of the motor response. This was proposed to incorporate only motor programming processes.

The primary problem was to study the effects of specific practice of portions of a perceptual-motor task on reaction time. A second problem was concerned with the effect of increased information load during perceptual practice and movement complexity during motor practice.

Hypotheses

The two hypotheses to be tested in this study are: 1) Specific practice of either the perceptual or motor components of the experimental task results in a decreased initial reaction time relative to a control group which experienced neither type of practice. 2) Increases in information load or movement complexity during practice of the perceptual or motor portions of the task, respectively, results in a decreased initial reaction time relative to a control group without practice and to the groups practicing the original perceptual or motor portions of the task. 3) Motor and complex motor practice results in a decreased movement time and movement time error relative to the no practice and perceptual groups.

Scope of the Study

Ninety-one subjects were randomly divided into five experimental conditions. Group 1 was a control group and received no practice on the perceptual-motor task. The other four groups performed forty practice trials in their specific conditions. Group 2 practiced only the perceptual portion (stimulus recognition and response selection) of the task. Group 3 also practiced the perceptual portion of the task with the addition of increased information load. Group 4 practiced only the motor portion of the task. Group 5 practiced a more complex modification of the motor portion of the task with the addition of a pause on a target located mid-way along the movement pattern.

All groups performed ten test trials on the original task which combined both perceptual and motor elements. Reaction time, movement time and movement time error were recorded on each trial.

Delimitations

The study must be considered within the following delimitations:

- 1) The subject population consisted of male and female subjects ranging in age from fifteen to forty years, with a mean age of twenty-three years.
- 2) Due to time limitations and the possibility of loss of motivation on the part of the subject, the number of practice trials was kept to forty and the test trials to ten.
- 3) The task consisted of recognition of a two colour light array and the performance of an associated movement pattern with the non-preferred hand.

Definition of Terms

The following is a list of terms which were used in the study:

1. Reaction Time was the time interval from the presentation of the stimulus until the initiation of a motor response.
2. Initial Reaction Time referred to the reaction time on trials one and two of the test trials.
3. Movement Time was the time interval from the initiation of the motor response until its completion.
4. Movement Time Error was the time during which the stylus held by the subject was off the movement pattern path.

CHAPTER II

REVIEW OF LITERATURE

The domain of reaction time research has encompassed a variety of topics. As a consequence, this review has separated the various studies into the following areas: a) Fractionation of reaction time into premotor and motor components, b) Psychological refractory period, c) Effect of movement parameters on reaction time, d) Influence of enforced motor and sensory sets, e) Hick-Hyman relationship, f) Stimulus-response compatibility, and g) Repetition effect. Though some of these concentrations may appear unrelated, other than their use of reaction time, they form a necessary foundation for the models of Sternberg (1969) and Theios (1975) which are central to this study.

Fractionation of Reaction Time into Premotor and Motor Components

The majority of reaction time research has considered the effect of different variables upon the total reaction time interval. The researchers made the implicit assumption that variations in total reaction time reflected variations in central processing. Though in most situations this assumption was valid, this was not always the case.

During the past fourteen years a portion of the research has dealt with the fractionation of reaction time into premotor and motor components. The time interval from the presentation of the stimulus until the onset of a muscle action potential (as measured by electromyography) was labelled as the premotor time. Motor time embraced the time interval from the initiation of a muscle action potential to the first sign of tension

uptake in the responding limb (i.e. the first observable movement).

In terms of information processing, premotor time was assumed to reflect central processing while motor time reflected peripheral delays in the musculature. Both have been found to be uncorrelated and independent (Lagasse & Hayes, 1973; Botwinick & Thompson, 1966; Schmidt & Stull, 1970). Premotor time and total reaction time have been found to have a high correlation, (Lagasse & Hayes, 1973), and thus it was assumed that in total reaction time reflected variations in premotor time or central processing.

Further support was derived from studies examining variables which have in the past been assumed to affect central processing. Three variables whose effect on premotor time was reflected in variations in total reaction time were anticipation, preliminary muscle tension and practice. Weiss (1965) and Botwinick and Thompson (1966), by manipulating the foreperiod, found that premotor time had the same functional relationship to foreperiod as did total reaction time. Motor time, however, was relatively unchanged across varying foreperiod lengths.

Schmidt and Stull (1970) studied reaction time in a situation in which the subject squeezed a hand gripping device to a preliminary muscle tension and then reacted to a stimulus by further increasing the force of contraction as quickly and as forcefully as possible. With increasing preliminary muscle tension, premotor time decreased, which supported the notion that preliminary muscle tension partially initiated a motor program for muscle contraction. Further increases in tension beyond the preliminary state were simpler, thereby shortening the central processing time. The motor time was lengthened with increasing preliminary muscle tension. The slower rate of tension development, motor time, was possibly

caused by the shortening of the muscle to a state of slightly shorter than 'resting length'.

A third variable which was used to study the relationship between premotor time and total reaction time was extended practice. Moris (1976) demonstrated that both total reaction time and premotor time decreased with practice. Motor time did not vary with performance across the practice trials. The decrease in premotor time supported the notion that extended practice increased the efficiency of central processing.

Several studies have examined the effect of muscular fatigue on the fractionated components of reaction time but with conflicting findings. Kroll (1973) found no effect on motor or premotor time, while others found a lengthened premotor time (Hanson & Lofthus, 1978) or a lengthened motor time (Stull & Kearney, 1978; Klimovitch, 1977). Kroll (1973) used bench stepping and isometric exercises to induce fatigue in the knee extensors. The levels of strength decrement did not exceed 24%, which might have accounted for the lack of effect on reaction time. The other three studies involved hand grip reaction time and used fatigue levels ranging from 20% to 60% strength decrements. The only procedural difference appeared to be the use of inter-collegiate athletes (tennis players and swimmers) by Hanson and Lofthus as opposed to university students.

In summary, it appeared that the variables that affected central processing such as anticipation (effects of varying foreperiod), practice and preliminary muscle tension, also affected premotor time. It was also demonstrated that premotor time was uncorrelated with and independent of motor time, but was highly correlated to the total reaction time. Motor

time was shown to be relatively invariant under most conditions except for moderate to high levels of muscular fatigue. As motor time remained relatively constant and was uninfluenced by variables that affected information processing, it was assumed that total reaction time could be used as a dependent variable to reflect changes in central processing.

Psychological Refractory Period

When a response was executed to each of two stimuli, separated by interstimulus intervals of 500 msec or less, the reaction time to the second stimulus was usually found to be longer than a single response to a single stimulus. This phenomenon has been referred to as the psychological refractory period (Welford, 1959).

Expectancy theory and single-channel theory were two explanations which have been proposed to account for this effect. According to an expectancy theory, the subject did not expect the second stimulus (S2) at very short intervals following the first stimulus (S1). Hence the arrival of S2 found the subject inadequately prepared and the reaction time to the second stimulus (RT2) was slow. Expectancy theory suggested that some minimum period of time was required to optimally prepare a response to the second stimulus. At intervals less than this minimum, preparation would be inadequate. As the inter-stimulus interval lengthened, the degree of preparation was increased and the delay in RT2 decline (Harison, 1960).

Single-channel theory stated that somewhere in the processing system, most typically at some control decision stage, there was a limiting mechanism which must process information in a successive manner. Thus reaction time to the second stimulus was delayed because the central

decision mechanism was occupied with the first response selection (Welford, 1959).

Many studies have examined the psychological refractory period in relation to the expectancy and single-channel hypotheses. The following studies dealt with the nature of the response to S2, different information levels of S1 and S2 and responses complexity, and their effects on the response latency to S1 (RT1) and to S2 (RT2). Their results supported the single-channel theory as opposed to expectancy theory.

Herman and Israel (1967) examined the effects of different levels of information of S1 (1, 2 or 3 bits of information, i.e. a two, four or eight choice paradigm) on RT2. In addition, the effects of S2 on the response latency to S1 (RT1) were compared when S2 signalled a response a) opposing that being organized for S1 or b) corresponding to that being organized for S1. The results indicated that under prior uncertainty of S1, S2 produced either decremental or facilitative effects on the latency of S1. An opposing S2 response increased RT1 whereas a corresponding response decreased RT1. It was concluded that a signal reinforcing a selected response reduced residual conflict and response latency.

Another series of studies employed a double stimulation paradigm. In this procedure two successive stimuli were presented, with a response required only for the first stimulus and not the second. Herman and Kantowitz (1969) presented S2 during the execution of the response to S1 (after an overt response to S1 had begun but before the entire response had been completed). These authors found no significant decrements in response latency to S1 or in errors in responding to S1 when compared with an independent control group who never experienced the second stimulus.

Herman (1969) modified the double stimulation paradigm so that performance could be examined under conditions of certainty and uncertainty. In this experiment, for two groups, an S2 light requiring no response was not presented or followed S1 at various interstimulus intervals ranging from 50 to 150 msec. For group 1, two lights were in a reciprocal relation as S1 and S2; if one flashed on first, the other became the potential S2 light. For group 2, the same two lights served as S1, but a third light was used exclusively for S2. A third group was never exposed to an S2 light. No delay in RT1 was observed if two successive lights signalled the same response, but a delay occurred if the second light was not clearly associated with the response to the first light. Herman (1969) concluded that the detrimental effect of S2 on reaction time to S1 would be observed under stimulus-response uncertainty if S1 and S2 elicit competing response tendencies.

Smith (1969) presented three experiments which examined the effect of varying information load on the response latencies to S1 and S2. By varying the number of alternatives associated with the first response and using a two choice paradigm for the second stimulus, it was found that RT2 increased with increasing levels of information of S1. In a second experiment the influence of varying information of S2 on RT1 was examined. It was found that the latency to S1 increased as the number of alternatives to S2 was increased.

A third experiment assessed the delay in RT1 in relation to a change in set (expectancy) or an increase in the amount of attention required to keep the second stimulus in memory. Increases in response latency were not found on trials where the subject was expecting the second stimulus but it

was not presented. The results suggested that some channel capacity was required for the maintenance of the second signal which Smith (1969) interpreted as support for the single-channel theory.

Other support for the single-channel hypothesis was reported by Siegel (1975). Siegel reasoned that the inflation in response latency to a complex response (Norrie, 1967, 1974; Glencross, 1972, 1973), reflected additional internal processing necessary to initiate the appropriate response. Single-channel and expectancy theories would have differing hypotheses concerning the effect that an initially complex response should have on the magnitude of RT2. Single-channel theorists would predict inflated RT2 values because the single-channel would be occupied by the additional time required to process S1, indicated by a longer RT1. Expectancy theorists would contend that RT2 should be unaffected by such increases in RT1, since RT2 would vary because of the subject's uncertainty as to the arrival time of the second stimulus. Siegel (1975) used a serial response task in which movement complexity of the first response was increased while the probability of a particular interstimulus interval occurring on any trial was held constant (i.e. the expectancy of S2's arrival was held constant). It was reported that reaction time to the second stimulus was longer when the initial response was complex as opposed to when it was simple.

In summary, single-channel hypothesis was supported. RT2 was increased as the number of alternative S1 stimuli was enlarged. RT2 was also increased due to an increase in response complexity to S1. Stimulus information level and response complexity would have affected different processes since the former involved stimulus processing and response

selection and the latter involved motor programming. Consequently there could have been two areas of limited channel capacity in the processes which occur during the reaction time interval.

The Effect of Movement Parameters On Reaction Time

In the choice reaction time experiment, the signal to respond informed the subject which of a set of possible responses was to be made. The task could thus be separated into two successive time intervals which have been subsequently studied. The reaction time interval began with the presentation of the stimulus and ended with the initiation of the response. Movement time began where reaction time ended and terminated with the completion of the motor portion of the task.

Movement time and reaction time have been shown to have a very low positive correlation (Henry, 1961; Mendryk, 1960) and have been proposed as being relatively independent processes (Fitts & Peterson, 1964; Laszlo & Livesey, 1977). A great many studies, though, have demonstrated specific relationships between reaction time and various movement parameters such as duration, distance and accuracy.

There were two difficulties which arose when the research literature in this section was reviewed. The first was in the diversity of the tasks used to study the effect of movement parameters on reaction time. These tasks ranged from limb movements of various magnitudes and degrees of complexity, to vocal responses. Though comparisons could be made on the basis of various movement parameters, the wide range of tasks affected the generality of the findings.

Secondly, the majority of authors dealt with the effect of movement complexity on reaction time. As yet, no one has presented a satisfactory definition of complexity. The literature cited movement duration, extent, direction, number of limbs, temporal sequencing, and resistance as factors affecting the 'complexity' of the movement. Both of the above impediments have limited the degree to which inferences might have been drawn regarding the relationship between parameters of movement and reaction time. Notwithstanding, the assumption was made that the focus of their effect would have been in the motor programming processes that occurred prior to movement initiation.

The following movement parameters were selected for review: duration, distance, direction, accuracy and number of limbs involved. It should be noted that many of the variables were studied in conjunction with each other and their results were subsequently confounded. Several studies about implicit speech were also included because implicit speech was not usually interpreted as a motor response and because the researchers were able to isolate the reaction time effects to the motor programming processes. Finally three explanations were considered which have been put forward to account for the relationship between movement parameters and reaction time.

Duration: Klapp and his colleagues have completed a series of studies dealing with the effects of movement duration on response latency. These studies used a morse code paradigm in which the subject responded with either a 'dit' or a 'dah'. The initial finding was that in a two-choice reaction time task, when the response was a 'dah', a longer reaction time interval occurred as opposed to when the response was a 'dit' (Klapp,

Wyatt & Lingo, 1974). An analogous effect was observed within a known sequence of two morse code responses for which the duration of the inter-response interval depended on whether the following response was 'dah' or 'dit' (Klapp & Wyatt, 1976). One would expect the relationship between reaction time and the nature of the response would be restricted to response sequences of fairly short overall length. If longer responses were not completely pre-programmed in advance, then later parts of a long response sequence may have been programmed during the response sequence rather than before it began. It was assumed that programming required time and could not occur concurrently with an ongoing response. Such programming should have been observable as a lengthening of the duration of the earlier phases of the response sequence as a function of the parameters of later phases. Apparently the subjects programmed the execution of the first 'dit' or 'dah' during the reaction time interval but programming of the second 'dit' or 'dah' was postponed until after the response was initiated.

The finding that responses of longer durations were associated with longer reaction times was again supported (Klapp & Erwin, 1976). They demonstrated that small changes in reaction time occurred when responses were varied in complexity and not duration while a larger change in reaction time occurred when the response duration was varied. The data supported a logarithmic relationship between programming and response duration. Therefore, Klapp and Erwin proposed that an acceptable theory of response programming must permit programming time to vary for constant response duration while still accommodating the possibilities that a) programming time could increase as a function of response duration alone and b) changes in response duration may be a necessary condition for the observation of large changes in programming time.

Distance: It should be noted in advance that very few of these studies controlled for duration. Thus there was a confounding of the variables since longer movements also had longer durations.

Henry (1961) used a simple forward movement to demonstrate that longer movements have correspondingly longer reaction times. Glencross (1973) using an elbow flexion task was able to replicate these findings. Studies using various other movements have not been able to replicate these results (Fitts & Petterson, 1964; Glencross, 1972; Lagasse & Hayes, 1973; Klapp, 1975). The difficulty in these replication studies have been the introduction of other variables as well as distance, notably the accuracy of movements to various target widths. The addition of accuracy might have influenced the subjects' motor programming which would have masked any effect of distance alone. A study which has shown a different relationship between response latency and distance was reported by Seigel (1977). Though not free from confounding with accuracy, a U-shaped relationship between distance and reaction time was demonstrated. Small movements (less than 50 mm) and larger movements (greater than 150 mm) had longer reaction times.

Some insight into the relationship between movement distance and movement duration can be achieved by considering a study by Schmidt and Russell (1972). In this experiment subjects were pretrained to make 22.8 or 49.5 cm. movements in exactly 150 or 750 msec. A 2 x 2 repeated measures design (movement time x movement distance) was used, and the index of preprogramming (Schmidt, 1972) was used to assess the degree of feedback involvement. Reducing the movement time from 750 msec to 150 msec nearly doubled the index of preprogramming, implying greatly reduced feedback control

(or more preprogramming) in the 150 msec movement. Doubling the movement velocity by lengthening the movement distance but keeping the duration constant had no effect on the index of preprogramming. It would appear that in terms of the amount of preprogramming necessary for the movement, movement duration was more crucial than movement distance.

It has been supposed that force might be the determining variable. Smith (1961) found that reaction time was highly specific to the limb involved which might be inferred as support that different masses of the limbs might be affecting reaction time. In terms of strength though, Glencross (1973) reported that increasing the resistance needed to be overcome for a specific movement did not result in significant increases in reaction time.

Direction: It too, was not free from confounding with movement distance and movement duration, but the results may be summarized as follows. In comparison to a direct forward movement to a single target, reaction time was found to increase for a movement that required a pause or a pause and reversal in route to a final target (Noirre, 1967, 1974; Glencross, 1972). This was not the case for movements that required a reversal without a pause on a definite target (Glencross, 1972, 1973).

Several authors have attempted to study the relationship between distance and the direction of a movement, but without any consistent results. Megraw (1972) had subjects control a horizontal lever to track a step input where the degrees of choice of direction and extent of movement were systematically varied. Increasing the choices of direction of movement from

1 to 2 led to an increase in reaction time of between 34 and 40 msec. No significant increase in reaction time was found as the choices of extent of movement were raised from 1 to 4. Kerr (1976) attempted to replicate Megaw's findings and found that response latency varied with extent uncertainty but not with direction uncertainty.

Accuracy: The accuracy of movements has been examined in terms of target width. Fitts and Petterson (1964) using a Fitts law paradigm task found that reaction time was relatively independent of target width. Klapp (1975) replicated these findings for movement lengths of 70 mm or longer. When shorter movements were used, reaction time was found to increase as the size of the target decreased. Klapp suggested that longer movements were under feedback control whereas shorter movements were predominantly programmed during the reaction time interval, with longer programming for more precise movements. The finding that reaction time was affected by target width was also supported by Seigel (1977).

Laszlo and Livesey (1977) used a different procedure than the Fitts law paradigm. In their experiment, subjects were presented with two rows of dots on a paper strip which moved towards them on a runway. Subjects were required to cross over a given number of dots in sequence with a pen, following an auditory signal. Reaction time was measured from the warning signal until movement initiation. Movement time was measured from the starting position to the first row of dots (MT1), and from the first row to the second row of dots (MT2). The control group began at the starting position and simply crossed over both lines of dots after the warning signal without crossing any dots. Group one had to cross over a dot on the first

line while group two had to cross a dot in both the first and second lines. In this way accuracy throughout the movement was manipulated by altering the number of dots to be crossed. Reaction time increased from the no dot to the one dot condition but not from the one dot to the two dot condition. Movement time increased from the one dot to two dot condition. The results suggested that reaction time involved some programming of movement initiation and thus was affected by increased accuracy. Movement time also included some programming of the ongoing response and was thus affected by the accuracy of the later stages of the movement.

Number of limbs involved: Henry and Rogers (1960) compared a finger movement with an arm movement and reported an increase in reaction time of about 20%. Norrie (1964) using simultaneous movements found that the reaction time for tasks involving an arm and a leg was slower than for tasks involving two arms. In comparison to a one limb movement, Glencross (1973) demonstrated that the response latency increased as the number of responding limbs increased.

Implicit speech: Studies in implicit speech have added a different dimension to movement-reaction time research. It was found that choice reaction time for pronunciation increased with the number of syllables to be pronounced. The relationship has been observed for printed or pictorial representations of words of matched frequency (Klapp, Anerson & Berrian, 1973), for two digit numbers and one to three syllable words (Erikson, Pollack & Montague, 1970; Klapp, 1971, 1974). The effect was attributed to programming the response and not to perception of the visual stimulus, since the time

required for perception was found to be independent of the syllable effect when pronunciation was not required (Klapp, Anderson & Berrian, 1973).

Possible explanations: Three interpretations have been offered by Henry and Rogers (1960), Glencross (1972) and Klapp and Erwin (1976) to account for the relationships between various movement variables and response latency. These explanations offered some insight into reaction time and how it was affected by movement, but they fell short in specifying the cognitive processes which were involved.

Henry and Rogers (1960): These researchers proposed a 'memory drum' theory of neuromotor reaction. This theory proposed a non-conscious mechanism that used stored information (motor memory) to channel existing nervous impulses from brain waves and general afferent stimuli into the appropriate neuromotor coordination centres, sub-centres and efferent nerves, thus causing the desired movement. The neuromotor details of a discrete single movement made at maximal speed were ordered by a stored program which was released by the stimulus presented. During the period that this program was being discharged to the muscles the response was resistant to modification. A new program, even though it involved different or antagonistic muscles, could not begin its outflow until the existing program has been read out, and refractoriness should be present during a considerable part of the movement at least. For simple movements, neuromotor discharge time should last only a few milliseconds and a stimulus would be able to release a second program within the response latency of the first response (Henry, 1961).

4

More complex movements, such as ones which occurred over a long distance and required maximal force, would necessitate a relatively intricate program.

Glencross (1972): Glencross (1972), suggested that response complexity could be considered in terms of the processes of effector discrimination and effector organization. Effector discrimination referred to the process of selecting or retrieving particular response units. In this case, a response unit was a muscle, or group of muscles, or a pattern of sensation which was represented in the brain and could be retrieved, or discriminated, and combined with other response units to form a response. Effector organization was the spatial-temporal patterning of selected response units.

Glencross proposed that the latency of a response would be related to the complexity of the effector discrimination and effector organization processes. Specifically latency would increase as a) the number of response units that have to be selected increases and b) the temporal sequences of the movement pattern became more involved and complex. For a complex response, a particular coded pattern of nervous discharge had to activate some particular set of response units. The larger the number of response units that had to be retrieved and combined, the longer it would take the coded pattern of innervation to traverse the neural pattern. If the movement involved a number of changes in direction and perhaps reversals, different response units would need to be active in a fairly precise temporal sequence. As the temporal pattern increased, the pattern of innervation would have also increased in complexity and would take longer to process. The significance of this approach lay in its ability to relate processing time to the selection of a particular number of response units, and also to the degree of temporal organization of the units.

Glencross (1972, 1973, 1976) has demonstrated some support for this theory. The strongest support came from the experiments which reported relationships between response latency and the complexity of the timing requirements of the movement. These findings were as follows:

1) Response latency increased as the number of timed movement segments increased (Erikson, Pollack & Montague, 1970; Klapp, Anderson & Berrian, 1973; Klapp, Wyatt & Lingo, 1974; Klapp & Erwin, 1976); 2) Reaction time was longer for the longer of the two possible required durations (Klapp & Erwin, 1976; Klapp, Wyatt & Lingo, 1974); 3) Reaction time varied in response to the timing requirements for components of the movement (Henry & Rogers, 1960; Glencross, 1973; Norrie, 1967, 1974); 4) Movements that required intermediate pauses on targets required longer to initiate than those that did not.

One of the major difficulties with Glencross' theory was the determination and manipulation of the response unit. It was questionable as to the number and degree of involvement of response units in such manipulations as timing, movement direction, extent and resistance.

Klapp and Erwin (1976): Klapp and Erwin prefaced their argument by stating that a theory of reaction time must be consistent with the findings for simple reaction time. In the choice reaction time paradigm the signal that marks the beginning of the reaction time interval also tells the subject which response was required. In the simple reaction time paradigm the response was identified earlier and the signal marking the beginning of the latency interval served only as a 'go' signal, which did not otherwise convey any information. Therefore, simple reaction time could be independent

of response parameters that influenced choice reaction time provided that the subjects were properly motivated (Klapp, Wyatt & Lingo, 1974). This would imply that the process responsible for the changes in choice reaction time could be completed in advance of the response signal by motivated subjects who have been informed which response was required.

A reaction time theory must also be consistent with the logical consideration that the process leading to changes in choice reaction time occurred even though the responses may have been highly over-learned and already represented in long term memory (i.e. speech). Therefore, the time dependent process must not reflect 'invention' of the response for the first time.

Klapp and Erwin's model assumed that programming transformed the long-term memory representation of the response sequence into a form that was suitable for the generation of commands to the muscles. They also proposed the existence of a short-term memory or temporary representation that was capable of generating motor commands without transformation. To account for the independence of simple reaction time from parameters that influence choice reaction time, it was assumed that the transformation was performed in advance and the new representation stored temporarily until the response signal appeared.

The transformation and temporary storage processes could be given a tentative neurological interpretation. It was assumed that timed commands to the muscles were generated by neural circuits involving multiple synapses and long pathways which provided time delays between the components of the response. Such circuits involved loops between the cerebral cortex and cerebellum (Rich, 1965, cited in Klapp & Erwin, 1976). As the impulse

moved along this pathway, motor commands were issued when certain points became activated. Since such circuits could generate the response commands, they could be identified with the transformed temporary mode of storage. This mode of storage would be used for temporary memory because such circuits would not be efficient for the long-term storage of many responses (Klapp & Erwin, 1976). Long-term memory was proposed to contain coded 'wiring diagrams' from which the temporary circuits could be generated by a transformation or programming process that required time. The long responses yielded increased choice reaction times because extended neural circuits would be required. Only a small increase in circuit complexity would be required to provide for the addition of response elements within a fixed overall duration.

To summarize, it was demonstrated that various movement parameters affected the reaction time interval. The parameters also formed an integral part of the movement itself. Therefore, it was concluded that the manipulation of the parameters resulted in an alteration of the motor programming processes which occurred prior to movement initiation.

Influence of Enforced Motor and Sensory Sets

One of the offshoots of the memory drum theory (Henry & Rogers, 1960) was the hypothesis that the neuromotor mechanism was nonconscious. Henry (1960) reasoned that any attempt to consciously control the movement would interfere with the nonconscious operating functions of the memory mechanism. As a result there would be increased reaction and movement times.

In operational terms, enforced set referred to instructing the subject to use only one set when performing the task regardless of personal

preference. Enforced motor set required the subject to concentrate solely on the movement required in the task. Enforced sensory set required that the subject concentrate on the stimuli that were to be presented. Furthermore, data was recorded only for those trials on which the subjects indicated that their attention conformed to the set enforced. It was found that enforced motor set resulted in longer reaction times and either slowed the movement (Henry, 1960) or had no effect on movement time (Christina, 1973).

The effect of instructions to respond quickly to a particular colour in a three-colour recognition task was studied in an attempt to determine whether the instructions operated to produce faster perception or faster response processing. While Henry (1960) and Christina (1973) used a simple reaction time paradigm, LaBerge, Tweedy and Ricker (1967) used a choice reaction time task. In their study, subjects responded with one hand to a green stimulus, and with the other hand to either red or blue stimuli. Their results showed large and consistent latency differences between emphasized and non-emphasized colours assigned to the same response. Since differential response bias was controlled in the design, the authors concluded that the instructed selectivity operated at the perceptual level.

Wiseberg and Pushkin (1976) extended the previous findings by examining response complexity in relation to enforced set. Their procedure involved three modifications of the response in a simple reaction time task. In the first phase, the response involved the raising of the index finger as quickly as possible. The second task involved a horizontal right to left arm sweep from a micro-switch to knock down a barrier. In the third phase the subject was required to make spatial and temporal shifts;

sequentially tapping three intermediate padded targets enroute to the barrier. Contrary to Henry (1960) and Christina (1973), Wiseberg et al (1967) suggested that motor set interacted with movement complexity. With simple movements, enforced motor set produced shorter reaction times while with complex movements it produced longer reaction times.

In summary, these studies support the assertion that there are at least two forms of selective attention, one corresponding to stimulus selection and the second to response selection.

The Hick-Hyman Relationship

Hick (1952) and Hyman (1953) demonstrated that reaction time was a monotonically increasing function of the amount of information in the stimulus series. The regression of reaction time upon the amount of information was the same whether the amount of information per stimulus was varied by altering the number of equally probable alternatives, altering the relative frequency of occurrence of particular alternatives or altering the sequential dependencies among occurrences of successive stimuli (Hyman, 1953). It was assumed that the responses of the subject were completely determined by the stimulus series, and the occurrence of successive stimuli did not alter the subject's knowledge of the statistical properties of the stimulus series as a whole. The function that best fitted this relationship had the general form of:

$$RT = a + b \log n \quad (\text{Hyman, 1953})$$

where n was equal to the number of equally probable alternatives used in the choice reaction time task.

The relationship has since been expressed as the information hypothesis. This hypothesis stated that all other things being equal (such as stimulus-response compatibility, training, discriminability and error rate), equal information conditions must produce equal overall mean reaction times. A weaker version of the hypothesis would have been that equal increments in information must produce equal increments in reaction time.

The linear function has been replicated under many different conditions (Archer, 1954; Gregg, 1954; Morin, Forrin & Archer, 1961; Alluisi, Strain & Thurmond, 1964; Krinchik, 1969). Of more interest to the present study were instances where this relationship failed to appear. Mowbray and Rhoades (1959) demonstrated that with sufficient practice (a total of 15,000 trials) there was no difference in mean reaction times to a two or a four choice reaction time task.

Leonard (1959) used a highly compatible stimulus-response task in which vibrations of relay armatures were presented to 1, 2, 4, or 8 fingers separately and the response was to depress the armature of the finger stimulated. The results showed a difference between simple reaction time and two-choice times, but no measurable difference in mean reaction times for the index finger were obtained between 2, 4, or 8 alternatives.

Seibel (1959) also employed a highly compatible task where each finger of the right hand was paired with a stimulus light. In response to the onset of one or more lights, the subject depressed the corresponding key(s). Stimulus sequences consisted of variously defined subsets of the 31 possible patterns and each subset varied in the number of patterns and in the particular patterns included. Reaction time was found to be highly

related to the particular pattern involved and independent of the number of patterns in the subset.

Several studies have described an absence of the Hick-Hyman relationship with responses that have a high degree of learning. Davis, Moray and Treisman (1961) described a series of experiments in which audio-verbal reaction times were recorded. Subjects responded by repeating what they heard, whether it was a digit or a letter. It was shown that the size of the group from which the signal was drawn had little effect on the reaction time to that signal.

Brainard, Irby, Fitts and Alluisi (1962) compared various stimuli (numerals and lights) and responses (vocalizations and finger movements) under different information conditions. Reaction time was found to be an increasing function of the average amount of information transmitted per stimulus-response event for three of the four stimulus-response pairings employed. Response latencies obtained from vocal responses to arabic numerals were affected only slightly by the number of alternatives in the range from 2 to 8. The lack of a Hick-Hyman effect further substantiated by the lack of a reduction in reaction time, resulting from a decrease in the number of alternatives for English language alphabets (Fitts & Switzer, 1962).

Morin and Forrin (1961) suggested that the linear relation between stimulus information and reaction time observed by Hyman (1953) could have been attributed to the confounding of stimulus, response and transmitted information. The amount of information per stimulus in a stimulus series was a function of the probability distribution of the possible stimulus events. Response information was also determined from the observed distribution of

responses. Transmitted information, on the other hand, depended upon the bivariate distribution of stimulus and response elements and reflected the association or lack of independence between stimuli and responses.

It was proposed that reaction time was a linear function of stimulus information, expressed in bits, for the special case in which response and transmitted information were each equal to stimulus information. Bricker (1955) had previously suggested that the amount of information an organism must process or transmit was the crucial determinant of reaction time. He contended that stimulus uncertainty, as such, was not crucial and suggested its relation to reaction time as a consequence of its confounding with transmitted information. Some support for Bricker's contention was provided by Morin and Forrin (1961). This study demonstrated that the presence of irrelevant stimulus information, which increased the perceptual demands placed upon the subject but did not alter the information measures, did not significantly influence the rate of information processing.

Morin and Forrin (1963) designed an experiment to assess the relative contributions of transmitted and response information. The choice reaction time task involved a 1-to-many mapping of stimuli onto responses. In the conditions with more than one response per stimulus, subjects were instructed to select randomly from available correct response alternatives. It was hoped that this procedure would affect a partial unconfounding of response and transmitted information. Differences in reaction time were found to be more clearly associated with differences in response uncertainty than with differences in the amount of information transmitted.

Kornblum (1968) has presented the argument that for a fixed

number of signals, the sequence of signals on which evidence for the information hypothesis was based were constructed in such a way that stimulus information increased simultaneously with the probability of non-repetitions (P_{nr}). Therefore, the observed increase in reaction time could have been attributed to an increase in P_{nr} and not simply an increase in information. This was of special interest since it has been shown that response latencies for repetitions were considerably faster than for non-repetitions (Bertelson, 1961, 1963, 1965). The mean overall reaction time distribution was simply the sum of the means of the reaction time for repetitions and non-repetitions, each weighted by its own probability of occurrence. Therefore, an increase in P_{nr} had the effect of increasing the proportion of slower responses in the overall reaction time distribution which in turn increased the mean of the overall distribution. Kornblum has supported this argument with a series of experiments (Kornblum, 1968, 1969, 1975) which have demonstrated that the function relating reaction time to the number of stimulus alternatives for repetitions did not follow the Hick-Hyman relationship, whereas the reaction time function for non-repetitions did. Thus, it was concluded that the effect on reaction time of increasing the number of alternatives was primarily a function of non-repetitions.

It should be mentioned that the information hypothesis specifies equivalent conditions only under conditions in which the subject has processed all the information available prior to the occurrence of each new stimulus. Hyman and Umiltà (1969) have asked if the conditions were optimal for such anticipatory processing on the part of the subject in Kornblum's 1968 study. They have suggested that since the subjects had to

deal with all eight conditions, they might have experienced possible interference. The extremely short inter-trial interval of 140 msec was also suspected not to give the subject adequate time to prepare for the next trial. Hyman and Umiltà (1969) used only three easily discriminable conditions and kept the inter-trial interval relatively long. Their results supported the information hypothesis.

In summary it would appear that the probability of occurrence of stimuli or responses was crucial in determining the reaction time. This probability effect would later become an important building block in the various reaction time models.

Stimulus-Response Compatibility

Fitts and Seeger (1953) stated that a task involved compatible stimulus-response relations to the extent that the ensemble of stimulus and response combinations comprising the task resulted in a high rate of information transfer. The degree of compatibility was maximum when recoding processes or transformations of the input information were at a minimum. Thus, Fitts and Seeger (1953) proposed that man's performance of a perceptual-motor task should be most efficient when the task necessitates a minimum amount of information transformation (encoding and/or decoding) or when the information generated by successive stimulus events was appropriate to the set of responses that must be made in the task (i.e. the set of responses was appropriately matched to the stimulus source). Thus, it would seem that the rate at which the perceptual-motor system could process information was a function, not so much of the characteristics of a particular set of

stimuli or a particular set of responses, but rather of the degree to which the sets of stimuli and responses form a congruent match.

Fitts and Deininger (1954) tested the hypothesis that one of the conditions of maximum stimulus-response compatibility was that the pairings of stimulus and response elements agree with a strong population stereotype. In this experiment stimulus-response compatibility was a function of the spatial relationship between the stimulus and the response. They found that the greater the spatial correspondence of stimulus and response sets, the more detrimental the effect of noncongruent stimulus-response pairings on choice reaction time.

Simon and Rudell (1967) used a series of experiments to demonstrate the existence of a strong population stereotype which affected the processing of verbal commands. In a choice reaction time task, the subject pressed the right- or left-hand key in response to the words 'right' or 'left' which were presented to the right or left ear. It was found that reaction time was significantly faster when the content of the command corresponded to the ear stimulated than when it did not. Therefore, information processing was affected by a cue irrelevant to the task itself; the ear in which the command was heard. Removing the subject's uncertainty regarding the ear to be stimulated resulted in significantly faster reaction times and reduced but did not eliminate the effect of the irrelevant directional cue.

Simon (1968) replicated these findings using a uni-manual choice reaction time task in which the subject moved a control handle to the right or left from the midline of the body. Both reaction time and movement time were found to be faster when the content of the command corresponded to the ear stimulated than when it did not. The response interference (or facilitation)

was apparently unrelated to sensory motor connections or hemispheric dominance since there was no interaction between the ear stimulated and handedness (Simon & Rudell, 1967). There was also no interaction between the ear stimulated and the responding member on either unimanual or bimanual tasks.

Simon (1969) employed the same apparatus but had subjects responding to the right or left depending on the ear in which they heard a 1,000 cps tone. Reactions toward the stimulus source were significantly faster than reactions away. Based upon this and their previous work, Simon concluded that the results showed a 'natural' tendency to respond toward the source of stimulation. When the source of stimulation corresponded with the response, a situation of high stimulus-response compatibility was created. The result was faster reaction times.

Another area of stimulus-response compatibility dealt with the spatial relationship between the stimulus and the response. Rabbitt (1967) with a simple horizontal stimulus light display, found that signal discriminability and stimulus-response compatibility interacted in their effects on choice reaction time. Evidently, the lamps nearer the centre of the display were more difficult to locate than were lamps at the extreme ends, and the effects of signal discriminability (the lamps spatial order) interacted with stimulus-response compatibility.

These findings were substantiated by John (1969) who used a ten choice horizontal display in a reaction time task. The results supported an inverted U-shaped relationship between reaction time and the position of the individual stimuli and responses within their respective arrays. Thus the discriminability of the individual stimuli of a unidimensional stimulus

array was a function of their position within the stimulus array and that in general, the stimuli nearest the centre of the stimulus array were the least discriminable as compared to the stimuli at either end. John (1969) proposed that performance in such tasks was mediated by an internalized representation of the whole stimulus array. Thus, it would appear that stimuli near the ends of the array were easier to differentiate, or in other words required less intermediary processing between the stimulus and the response. This would not be true of the stimuli in the centre of the array, and hence their longer reaction times. Therefore, this example of stimulus discriminability could also be interpreted in terms of stimulus-response compatibility.

There have been many applications of the stimulus-response compatibility effect, but only two will be considered at present. Alluisi, Strain and Thurmond (1964) examined stimulus-response compatibility and the rate of gain of information. Their subjects responded vocally at three levels of stimulus uncertainty to visually presented arabic numerals. Responses were paired with the stimuli in three ways to create ensembles of high, intermediate and low compatibility. Response latency was found to be an increasing linear function of the amount of information transmitted. The degree to which reaction time was influenced by transmitted information was found to be an inverse function of the degree of stimulus-response compatibility. Thus, the lower the stimulus-response compatibility, the greater the effect of transmitted information on reaction time. This stands to reason if low compatibility was equated to a greater degree of information transformation occurring between stimulus and response. Thus, information

processing of several alternatives would be further complicated and result in longer response latencies.

In summary, the importance of the amount of processing required by each stimulus-response unit was demonstrated. As the number of transformations of information increased, the reaction time was lengthened. The concept of transformation of information from one form to another was an integral part of the various processes which occurred during the reaction time interval.

The Repetition Effect

Bertelson (1961) used a self-paced two choice serial responding task which involved two neon lamps as signals and two response keys in simple spatial correspondence with the signals. The purpose of the experiment was to compare the effects of varying amounts of sequential redundancy on reaction time. His finding, which has since been called the repetition effect, demonstrated that reaction times to repeated signals were faster than when the preceding signal was different.

In the original experiment the degree of stimulus-response compatibility was high. Bertelson (1963) compared three levels of compatibility with responses to new and repeated signals. Both types of reaction times increased with decreasing stimulus-response compatibility but the effect was larger on the reaction times to new signals. This result was further substantiated by Schvaneveldt and Chase (1969) who found with less compatible stimulus-response codes, repetitions facilitated reaction time in both two and four choice tasks only after two repetitions. With a highly incompatible four choice task, one repetition was sufficient to

facilitate reaction time maximally. It would appear that the repetition effect was greater for less compatible stimulus-response arrangements.

In contrast to the above studies, experiments which have used a discrete two choice reaction time paradigm have typically found negative recency, that is responses to repeated signals were slower than to new signals. Williams (1966) found that the responses to a changed signal were about 35 msec faster than to repeated signals. A similar small negative recency effect was also reported by Hyman (1953).

The existence of the repetition effect has been demonstrated by many studies and has generated a great deal of research in regard to the basis of the phenomenon. Bertelson (1963) suggested that either a) different mechanisms were involved in reactions to repeated signals and in reactions to new signals, or b) the same mechanisms were involved but worked faster in the case of repetitions, due to some sort of facilitative after-effect. The addition of the stimulus-response compatibility studies suggested that the reactions to new signals involved processes whose durations depended in some way on the stimulus-response relationship. The reactions to repeated signals, however, could be organized via a shorter process with the duration independent of the stimulus-response relationship.

The typical stimulus-response paradigm used for demonstrating the existence of the repetition effect involved a 1-to-1 mapping of stimulus onto response. Thus, during the repeated trial, both the stimulus and its accompanying response were repeated. If it was assumed that there were separate processes related to stimulus processing and response processing, then the repetition effect could have been the result of either repetition

of the stimulus, the response or both. Consequently a large number of studies have examined independently the manipulation of stimulus and response probabilities or occurrence.

A specific experimental design was employed to study the effects of different stimulus and response frequencies upon reaction time. The design involved the use of three stimuli and two responses. One response had two stimuli associated with it while the second response had only one stimulus. The frequency of the various stimuli could be studied independently of the response frequency.

Laberge and Tweedy (1964) analyzed a two response colour identification task. The subjects responded with one hand to a green light and with the other hand to either a red or a blue light. When the red and blue presentation ratio were shifted from 1:5 to 5:1 the response latencies to these colours shifted in such a way that the more frequent stimuli always yielded the faster latency.

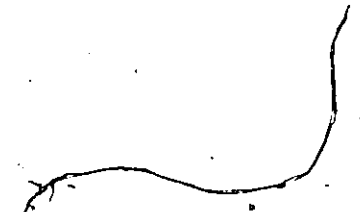
Bertelson (1965) compared the response latencies of repetitions of different stimulus-response codes (different stimulus and response), identical stimulus-response codes (same signal and same response) and equivalent stimulus-response codes (different signal and same response). He demonstrated that the reaction times for 'different' trials were greater than for equivalent and identical trials. The response latency for identical trials was only slightly but consistently shorter than equivalent trials; showing a reliable response repetition effect (Bertelson, 1965; Rabbitt, 1968).

Bertelson and Tisseyre (1966) modified the above procedure so that stimuli of equal frequency were associated with responses of unequal

frequency. In this study four stimuli and two responses were used. The results demonstrated that the relative frequency of the response did not affect reaction time. The critical variable appeared to be the relative frequency of the stimulus. This fostered the suggestion that the reduction of the response latency was due to the preparation of the early stages of the information processing mechanisms, those concerned with the identification of the stimulus. Smith (1968) used the same procedure and was able to replicate their results.

LaBerge, Legrand and Hobbie (1969) replicated the original LaBerge and Tweedy (1964) study but analyzed the results in a different manner. The purpose of the study was to explore the possibility that both perceptual and response biasing may have operated in this task. Biasing was produced principally by increasing the relative frequency of one stimulus or response while keeping the frequencies of the other stimuli or response constant. Perceptual bias was measured by subtracting the response latency to the more frequent stimulus of one hand from the latency to the less frequent stimulus of that same hand. Response bias was measured by subtracting the response latency of the less frequent stimulus of the one hand from the latency of the sole stimulus on the other hand. Differences in the mean response latencies suggested the existence of both perceptual (stimulus) and response effects. Further support was offered by Bederman and Zachary (1970) who used the same method of analysis.

A study by Hawkins, Thomas and Drury (1970) replicated the essential features of the LaBerge, Lagrand and Hobbie (1969) study with the exception that a discrete reaction time paradigm was used. The results



indicated that the reaction time effects attributed by LaBerge to bias in the response selection phase of information processing may have been unique to the serial reaction time situation. Along with Bertelson and Tisseyre (1966) and Hawkins and Hosking (1969), stimulus rather than response probability was the major factor producing relative frequency effects in discrete choice reaction time tasks.

In summary, the repetition of the stimulus seemed to account for more of the repetition effect than repetition of the response. The frequency of response repetition could not be completely discounted since in certain cases such as serial versus discrete tasks, it appeared to be a large contributor. Overall, it seemed that the repetition effect was a stimulus effect and hence could be localized to one of the stimulus stages of processing. One possible explanation was derived from the trace decay theory. This hypothesis held that when a stimulus occurred, the subject first compared it to the still present but decaying sensory trace of the preceding stimulus. If the present stimulus was identical to the preceding one, and the preceding one's trace had not undergone extensive decay, then a match would occur between the trace and the stimulus. Therefore, the subjects would not have to engage in a relatively long-duration comparison process to categorize the repeated stimulus, whereas they would when categorizing a non-repeated stimulus whose matching sensory trace would be unavailable. This argument would lead to the prediction that the repetition effect would decrease in magnitude as the time interval between the preceding response and the repeated stimulus (inter-trial interval) was increased.

A series of studies have investigated the repetition effect with inter-trial intervals ranging from 50 msec to 10 seconds. Bertelson (1961)

originated the work with the finding that the repetition effect was reduced when an inter-trial interval of 500 msec was used. Bertelson and Renkin (1966) extended the inter-trial interval to 1000 msec and reported similar results. Since then, several authors have replicated and substantiated the original finding that the repetition effect decreases with the passage of time (Hale, 1967; Smith, 1968; Umiltà, Snyder & Snyder, 1972; Smith, Chase & Smith, 1973).

If the repetition effect was due to the activation of a short-term trace similar to that postulated to underlie short-term verbal memory, then as the interval between presentations was increased there would be an increased fading of the memory trace or perhaps increased interference by other traces. As a result there was a greater likelihood that the subject would initiate a search process to select the correct response. Consequently with longer inter-trial intervals the difference between reaction time to repeated and non-repeated events should decline. Since there was a greater necessity of going through a search on each trial, one would have expected mean reaction time to increase as inter-trial interval was increased.

Smith, Chase and Smith (1973) studied repetition effects as a function of the inter-trial interval in a four stimulus/two response reaction time task. Repetition effects were varied by repeating (on adjacent and non-adjacent trials): a) both the stimulus and the response, b) only the response, or c) neither. The response repetition effect was estimated by the reaction time difference between c) and b) while the stimulus repetition effect was given by the difference between a) and b). An analysis that considered repetition effects only across adjacent trials performed by Bertelson (1965) showed the occurrence of stimulus and response effects,

both of which declined with inter-trial interval (Eichelman, 1970). Although this was consistent with the hypothesis that repetition effects were mediated by a rapidly decaying trace, a further analysis that considered repetitions over both adjacent and non-adjacent trials revealed primarily stimulus (rather than response) repetition effects; some of which did not consistently decrease with inter-trial interval. Smith, Chase and Smith argued that the results of this more extensive analysis were consistent with the hypothesis that repetition effects reflected a self-terminating memory search rather than a trace decay phenomenon. The memory search hypothesis assumed that the categorization of any stimulus involved a sequential search of short-term memory, where the order in which the memorial alternatives were compared to the stimulus was probabilistically determined by how recently these alternatives had occurred (Theios, Smith, Haviland & Traupman, 1973). This hypothesis clearly accounted for the adjacent stimulus repetition effect since the last alternative presented was frequently among the first ones searched. As the inter-trial interval lengthened, there was an increasing probability that some task-irrelevant stimulus (produced either externally or by the subject) would enter short-term memory. This would lower all of the memorial representations in the search order and consequently reduce stimulus repetition effects.

An alternative explanation proposed to account for the repetition effect was the anticipation hypothesis. The subject attempted to anticipate what the next stimulus would be and retrieve from memory the associated response. Then if the 'guessed' stimulus did occur, the subject needed only to initiate the response already retrieved which would result in some saving

of time. If, as Bertelson (1963) suggested, subjects tend to check for a repeated stimulus, then the saving in time would occur more often to repeated stimuli. Keele (1969) suggested that when subjects anticipate the stimuli they also retrieve or partially retrieve the corresponding response hence more time is saved.

Schvaneveldt and Chase (1969) have also suggested that the advantage of repetition was the result of anticipation strategies. They found that reaction time was not determined so much by the preceding stimulus occurrence as by the preceding sequence of stimuli. This proposal was substantiated by Remington (1969) who demonstrated the existence of the repetition effect in fifth-order sequences.

In order to study the anticipation hypothesis, the standard repetition effect experimental paradigm was modified to include a verbal prediction of the next stimulus. The use of verbal reports in a choice reaction time to study the expectancy hypothesis has shown significant decreases in response latency to correctly produced stimuli (Bernstein & Reese, 1965, 1967). Hinrichs and Krainz (1970) employed this manipulation in the original three stimuli/two response paradigm. Mean reaction times were significantly faster only when the stimuli were correctly predicted. Reaction times to an incorrectly predicted stimulus, with the same response as the correctly predicted stimulus, did not differ from the reaction times to a stimulus with a different response. The results indicated that the expectancy effect observed - that correct predictions were associated with faster reaction times than incorrect predictions - could be attributed to the correct anticipation of the stimulus rather than to the preparation to execute the

correct response. Thus, reaction time to a stimulus was not improved by the correct anticipation of the response to be executed unless the correct stimulus was also anticipated. This agrees with previous findings that stimulus repetition may be the prominent factor in the repetition effect.

Though the expectancy or anticipation hypothesis has been supported by other researchers (Williams, 1966; Hale, 1967; Keele, 1969; Schvaneveldt & Chase, 1969) it was questionable what this interpretation offered. In terms of information processing it was possible that the anticipation of a stimulus might be related to it having a greater probability of occurrence, and thus, how it would be stored in a probabilistic oriented storage. If this was the case need we talk about 'anticipation' per se?

The final area of the repetition effect was devoted to a series of unique studies conducted by Rabbitt. Considered as a related group of experiments, it outlined several fascinating possibilities of the repetition effect which have been relatively ignored by other researchers.

Rabbitt (1965) reported that responses following responses made with the same hand were significantly faster than responses following responses made with the opposite hand. As the probability of alternations between hands was greater than the probability of repetitions of the same hand, this effect cannot be due to expectations based on the learning of the transition structure of the signal sequence presented. Thus, this data showed that a response repetition effect may be obtained when neither a particular response nor a particular sequence of muscle movements was repeated. A sufficient common feature appeared to be the selection of the limb with which the response was made. Bertelson's (1963) results implied, though, that this effect could not be related to transient improvements in muscular

tone in a limb which was recently used. Thus, the effect in this case must depend upon the repetition of only part of a series of decisions in the central nervous system, which may collectively be called the 'program', for the selection and organization of a response. Further study (Rabbitt, 1966, 1969) allowed Rabbitt to suggest that the repetition effect, in part, depended upon the learning of a rule associating signals to responses. When this rule was unfamiliar or was made more difficult, learning was slower.

Consequently Rabbitt has proposed three different stages at which the repetition effect may occur: a) repetition of a stimulus (perceptual processing), b) repetition of a response (motor programming and response execution), c) repetition of a rule relating members of a common signal set to the same response.

Rabbitt (1965, 1967) demonstrated that some repetition effects did not depend upon repetitions of identical signals or responses. It seemed that they occurred because some transitions between motor acts were easier than others. Thus, the sequential effects appeared to be mediated by the repetition or partial repetition of the motor programming sequence intervening between the encoding of the signal and the execution of a motor response to it. Thus, the suggestion of a rule repetition effect.

Rabbitt and Vyas (1973) concluded that neither the complexity and the consequent duration of processes of signal identification and classification, nor the complexity and duration of processes of response selection and execution were independent of learned coding rules intervening between these processes. The application of these rules was facilitated by repetition and their nature was possibly changed by practice.

Rabbitt, Fearnley and Byas (1975) and Rabbitt, Chancy and Vyas (1977) have suggested that the stimulus-response connection systems and response programs were not independent. Thus, it would be possible that the level of activation in one system would affect the level of activation in the other system. Facilitation of one stimulus-response connection system, might involve some corresponding 'facilitation' or 'inhibition' of others.

A feasible comparison seemed to occur with tasks in which subjects must on some trials refrain from making any response at all while on other trials they respond to other signals presented to them (Rabbitt et al, 1977). It was possible that the subjects experienced inhibition when they had to make a response to a signal which followed another signal to which they had to withhold any response at all. Thus any proposed model must account for such inhibiting effects and accordingly must postulate interactions between stimulus-response connection systems.

To summarize, the repetition of a stimulus, a response or the relationship between the stimulus and response resulted in decreased reaction times. The existence of the repetition effect implied that there were at least three areas in the reaction time processes where the efficiency could be increased through repetition: 1) stimulus encoding and identification, (2) motor programming, and 3) response selection (based on the stimulus-response relationship).

Models of Reaction Time

The preceding sections of the review of literature have dealt with different concentrations of reaction time research. On this foundation, several models have been proposed in order to specify the nature of the

processes which occurred during the reaction time interval. Though a variety of theoretical positions have been proposed, (Smith, 1968), only two recent models were considered. Sternberg (1969) and Theios (1975) each proposed a series of successive processes which occurred between stimulus presentation and response initiation. Both models concentrated on the method of search used in the response selection processes as the central hypothesis for their models. Sternberg (1969) proposed a serial-exhaustive search whereas Theios (1975) hypothesized the presence of a self-terminating search. The remainder of their models described similar processes, but Sternberg's model was viewed as a preliminary step towards the more extensive model of Theios.

Sternberg's Model

Sternberg (1966, 1967) modified the traditional choice reaction time paradigm to form a new character-classification task. In this experiment the subject memorized a small set of characters called the positive set. On each of a sequence of trials a character was presented as the test stimulus. The subject made a positive response if the character was a member of the positive set and a negative response otherwise. The size of the positive set was the critical independent variable while reaction time, the dependent variable.

Sternberg's initial findings demonstrated that reaction time increased linearly with the size of the positive set (Sternberg, 1966). The linearity and the slope of the function implied the existence of an internal serial-comparison process, whose average rate was between 25 and 30 symbols per second.

Sternberg (1967a) modified the above procedure by requiring the subject to name the item that followed a test item in a short memorized list (positive set). Thus, the test item had to be located in the list since its context was to furnish the required response (the name of the item that followed the test item). The results indicated that the mean reaction time increased linearly with the size of the positive set. The linearity and the slope of the function relating mean reaction time to the size of the positive set and the effect of the test item's serial position implied that the test item was located in the memorized list by an internal self-terminating scanning process whose average rate was 4 items per second. Sternberg (1967b) repeated his character classification experiment but used test stimuli that were either in tact or degraded by a superimposed pattern. The results indicated that degradation of the stimulus influenced mean reaction time and the slope of the function and its intercept.

The results of the above experiments on character classification support, according to Sternberg (1967b), a theory of high-speed scanning in memory. According to this theory, the time between stimulus and response was occupied, in part, by two processes related to the recognition or classification of a character. The first encoded the visual stimulus as an abstracted representation of its physical properties. The second, which may occur more than once, compared such a stimulus representation to a memory representation, producing either a match or a mismatch. This process was hypothesized to be an exhaustive serial-comparison process. A representation of the test stimulus was compared successively to a sequence of memory representations, one for each member of the positive set. Each successive comparison had the same duration and resulted in either a match or mismatch.

After completion of the search, a positive response was initiated if there was a match and a negative response if a mismatch occurred.

Sternberg (1967b) listed several findings which support the exhaustive scanning theory. The mean latencies of both positive and negative responses increased linearly with the number of characters in the memorized set. This finding was supported for sets of up to six characters with ensembles of digits or letters. The mean increase in latency per character was approximately the same for positive as for negative responses. This equality suggested that the search was exhaustive rather than being terminated when a match occurred. The magnitude of the latency increase indicated an average rate between 25 and 30 characters per second. Lastly, although the size of the positive set affected reaction time the size of the full ensemble did not.

Mean reaction time (RT) plotted as a function of the size of the positive set (s) could be exemplified by the following equation:

$$RT = \alpha + \beta s$$

The slope β represented the mean time taken by the comparison of the stimulus representation to the memory representation of one character (operation 2). The intercept α measured the mean time taken by events before and/or after the series of comparisons (operation 1). Operation 1 occurred only once while operation 2 may have occurred several times, once for each character in the positive set.

The results of the Sternberg (1967b) study showed that degradation affected operation 2 as well as operation 1. Visual degradation could influence the comparison operation only if there were residual degradation in the stimulus representation. Therefore, it would follow that the memorial

representation used in operation 2 consisted of the physical properties of the stimulus rather than its identity or name. Thus, identification need not occur prior to classification.

As a result of the experiment examining the location of the item in the positive set list (Sternberg, 1967b), a preliminary model was suggested (Sternberg, 1967a). In the retrieval of contextual information (i.e. information regarding location), the test item must first be located in the memorized list. Sternberg suggested that this was achieved by a self-terminating process of scanning. The test item was compared successively to the items in memory until a match occurred. When the next item was to be named, the search was shifted from the test item to the adjacent response item. The mean time from the beginning of one comparison to the beginning of the next, and the mean time to shift were affected by neither list length nor serial position.

To account for why locating an item in a list took so much longer than to determine its presence, Sternberg proposed the following model. Suppose a retrieval system in which a) the occurrence of a match, but not the location of the item that produced it, was entered in a register if and when it took place, b) a separate operation of checking the register was required for detecting whether a match occurred, and c) the checking operation was slow and could not occur concurrently with the comparison operation. In such a system, self-terminating search would entail a long interruption after each comparison to check the register. When the required response depended only on the presence or absence of an item, sufficient information could be obtained by checking the register just once, after performing comparisons throughout the entire list. Although this would

increase the mean number of comparisons on trials requiring positive responses, nonetheless, it could yield shorter reaction times than the self-terminating search.

Sternberg (1969) proposed a new method for using reaction time measurements to study stages of information processing. The method was called the additive factor method and Sternberg used it to lead to a four stage model. Donder (cited in Sternberg, 1969) initially suggested that the existence of successive functional stages between the stimulus and response whose durations were additive components of the total reaction time. With this as an initial assumption, Sternberg suggested that additivity could be tested for by evaluating the linearity of the function relating reaction time to the number of elements scanned. The slope of the function represented the mean time to scan one item and its zero-intercept represented the combined durations of all events other than scanning.

Sternberg proposed that when factors influence no stages in common, their effects on the mean reaction time would be independent and additive because the stage durations were additive. Thus, the effect of one factor would not depend on the levels of the other factors. A factor was an experimentally manipulated variable or a set of two or more related treatment levels. The effect of the factor was reflected in the change in the response measure induced by a change in the level of that factor. When two factors influenced the same stage, there was no reason to expect their effects to add. The most likely relation would be some sort of interaction.

With the additive factor method the search was for pairs of factors that had additive non-zero effects. Whenever two such additive factors were discovered, it was reasonable to hypothesize that there existed a

corresponding pair of stages between stimulus and response. Conversely, if a pair of additive factors that corresponded to a pair of hypothesized stages interacted, this may be taken as evidence against the hypothesis.

A stage in information processing was conceptualized as a series of successive processes that operated on an input to produce an output and contributed an additive component to reaction time. The concept of additivity entailed a property of independence for mean stage durations. The mean duration of a stage depended only on its input and the levels of factors that influence it and not directly on the mean durations of other stages. As well as the additivity among the factors, the patterns of interaction also yielded information. The subsets of interacting factors associated with a stage and the ways they interacted might suggest the operations performed by that stage, possibly its location in a series of stages and its internal structure.

Sternberg (1969) has suggested four other features that might be incorporated in a formal definition of a stage: a) given its input, the output of a stage should be independent of factors influencing its duration (this requirement would preclude indirect factor effects), b) the stages in a series should be functionally interesting and qualitatively different and should 'make sense' in terms of other knowledge, c) a stage should be able to process no more than one 'signal' at a time, d) stage durations should be stochastically independent.

The four factors Sternberg found in his studies which had additive effects were stimulus quality, size of the positive set, response type (positive or negative response) and relative frequency of response type. Sternberg reasoned that the stage influenced by stimulus quality was most simply interpreted as a preprocessing or encoding stage, which prepared a stimulus representation to be used in the serial-comparison stage. This

stage was proposed as being distinct from serial-comparison because stimulus quality influenced reaction time without affecting the time per comparison (slope of reaction time function). The two factors were additive rather than interactive. The purpose of the serial-comparison stage was thought to provide information for response selection, and consisted of substages corresponding to each of the comparisons of the positive set. The stages influenced by response type and relative frequency of response type, which depended on this information must have followed the serial-comparison stage. Finally, Sternberg suggested that since stimulus quality influenced a stage that preceded serial-comparison and relative frequency influenced a stage that followed serial comparison, these two factors must have influenced two different stages. Figure 1 presents a graphic interpretation of Sternberg's model.

In considering the limitations of his model, Sternberg (1969) suggested several possible restrictions of the factor additivity method. Although instances of additivity of factor effects led to the postulation of separate stages, other considerations were necessary to determine the order in which these postulated stages occurred. Any analysis produced by this method must be tentative. If a new factor was discovered that interacted with none of the others then an additional stage must be hypothesized. New factors that interacted with one or more of the others may lead to redefinition of the functions of particular stages. The additive factor method did not lead to information regarding the total duration of a stage.

Several of Sternberg's assumptions appeared to be crucial for the success of his model. As a consequence, they have come under considerable

FACTORS THAT AFFECT EACH STAGE

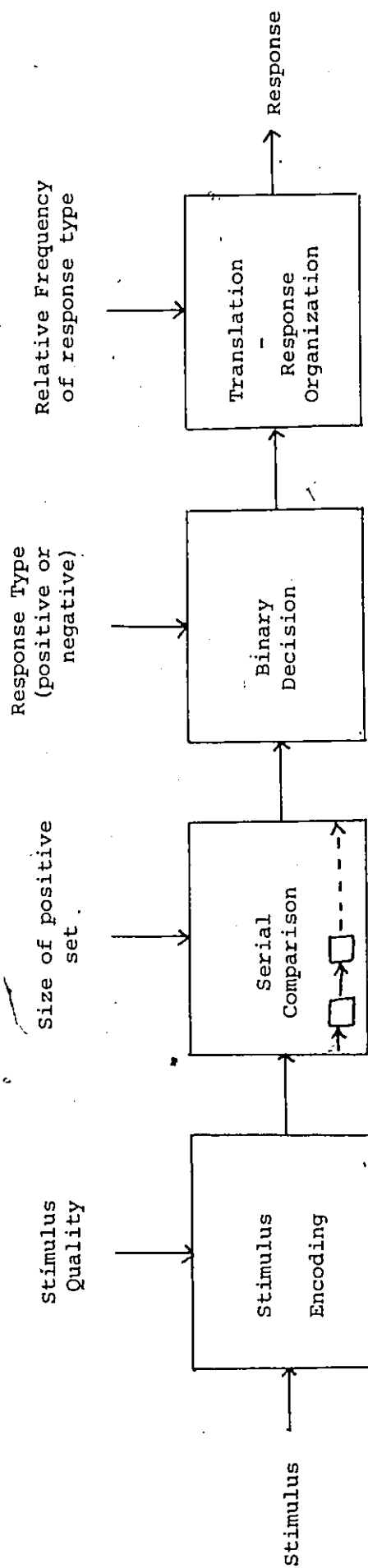


FIGURE 1: Sternberg (1969) Reaction Time Model

scrutiny by other researchers. There were three areas where Sternberg's model had difficulty in accounting for the experimental findings. These areas were as follows: 1) The effect of the probabilities with which different items of the positive set were presented as test stimuli, 2) The repetition effect and 3) Serial position effects.

Perhaps the most critical criticism of Sternberg's studies was the possible confounding of the manipulation of the positive set size and the probability of occurrence of a specific positive set item. The possibility of a probability effect first arose with the examination of a serial position effect in the Sternberg experimental paradigm. Morin, DeRosa and Stultz (1967) employed a recognition task and found that reaction time was markedly influenced by the serial position of the items. Especially noticeable was the large recency effect. An exhaustive search would have dictated that even though the test stimulus may have matched a member of the positive set, the comparison process was perceptual until all the positive stimuli in memory have been evaluated. There was no basis within Sternberg's theory to anticipate differential reaction times to members of the positive set. These findings would support a theory with a self-terminating characteristic in its search.

Implicit in most interpretations of choice reaction time data was the assumption that the anticipatory adjustments producing probability effects in reaction time were determined by the informational properties of the total stimulus-response array. Hawkins and Hosking (1969) varied the likelihood that a pair of unequally probable stimuli would appear in the positive set across conditions by manipulating the pattern of stimulus-response correspondences. Under these conditions reaction time increased

with positive set size but was uninfluenced by negative set size, suggesting that only the positive set had been maintained in memory and examined prior to response initiation. In this study the subjects selectively preattended to only a portion of the total population of available relevant stimuli (i.e. the positive set). This strategy may have been optimal because it minimizes the number of alternatives the subject must keep track of in memory and interrogate prior to response selection. For probability effects to exhibit themselves in reaction time, the manipulated items must be stored in memory. If the size of the positive set exceeded the size of the negative set, then it would be possible for the subject to adopt the strategy of committing the negative set to memory since this would reduce memory load (Wingfield & Branca, 1970). Thus, membership to positive or negative sets did not necessarily determine which items would be stored in memory.

Three studies have demonstrated that the probability of occurrence of the positive set items affected mean reaction time. Marcel (1970) varied the size of the positive set but kept the size of the negative set constant. The Sternberg procedure was modified by selecting digits based on their serial order rather than random selection. The results, when analyzed per group, demonstrated a serial effect as if the subjects searched the digits in analogue fashion to their overlearned set order. Theios, Smith, Haviland, Traupmann and Moy (1973) extended Marcel's study by independently varying probability of occurrence and memory set size. Further analysis demonstrated that for every memory set size from two to five, for both positive and negative stimuli, there was a systematic decrease in mean reaction time with increases in stimulus probability. This finding was further substantiated in a study by Theios and Walter (1974), where mean reaction time to both

positive and negative stimuli was found to increase approximately 85 msec as stimulus presentation probability decreased from .30 to .05.

An interesting modification of the Sternberg classification task which imposed a concurrent load on long- and short-term memory, was conducted by Forrin and Morin (1969). For long-term memory the class assignment remained constant throughout the course of the experiment. For short-term memory new items were specified on each trial. The functions relating reaction time to set size for positive and negative responses did not have equivalent slopes. Consequently, the condition for an exhaustive search was not met. The results also seemed to support the contention that the two sets of items (long- and short-term) were maintained in memory stores sufficiently distinct that one may be operated upon independently of the other.

A more serious fault with Sternberg's model was its failure to account for the repetition effect especially over adjacent trials. If a subject always tested for all signals, there would be no reason why repetition of an identical signal should result in faster reaction times than repetition of an equivalent signal (Rabbitt, 1968; Smith, Chase & Smith, 1973). It would seem that a self-terminating routine would be more applicable. In this case it could be assumed that the first test of a series was always for the signal which had last been successively identified. This notion would be consistent with a self-terminating search in which the order of the items was probabilistically determined by how recently the alternatives have occurred (Theios, Smith, Haviland, Traupmann & Moy, 1973).

A final area of concern lies with a group of studies which have used different types of stimuli than the conventional letters and digits. The task was similar to that used by Sternberg (1966). The subjects were given a stimulus and were required to state whether or not that stimulus was present in a previously memorized list. The stimuli consisted of words and pictures. If the first letter of the word, or of the name of the picture, was a member of the memorized set then a positive response was made. This task involved a search of long-term memory and translation. For example, if given a picture, the subject had to retrieve the name of the picture from long-term memory, translate that name to its first letter and then transform the letter into a form that could be compared to the memory set representation before searching for a match. Combining the task so that words and pictures were presented together in random sequence complicated the task to such an extent that it was difficult to separate the effects (Klatzky & Atkinson, 1970).

Klatzky, Juola and Atkinson (1971) and Gaffan (1977) replicated the above study but presented exclusively letters, exclusively pictures or random sequence of both. It was found that the letter and picture sessions supported the serial exhaustive search but the functions for the mixed sessions deviated markedly from the equal slope prediction of the exhaustive model.

In an exhaustive search the same number of comparisons were made for both positive and negative responses. Therefore, the slopes of the reaction time functions would be equal (or have a ratio of one). In the self-terminating case the subject must search on the average only one half

of the memory set before making a positive response, whereas he must search the entire set before making a negative response. Therefore, the slope of the positive function would be half that of the negative function (or have a ratio of two). The data for the mixed sessions departed from the exhaustive scan prediction. The analysis of the data per block of trials yielded a slope ratio of 1.4 for both pictures and letters for the first two blocks. In the third block the slope ratio for letters was .97 and for pictures 2.25. With practice it appeared that letters have an exhaustive scan while pictures a self-terminating scan.

Additional information was obtained from the serial position curves. A function with a slope of zero (i.e. no serial position effect) would support an exhaustive scan model. If the curve had a random starting position a self-terminating process would be indicated. However, the curves exhibited an increasing trend which would imply that some self-termination was occurring even though the slope ratio for negative and positive responses was close to unity. This would have suggested that a distinction between self-terminating and exhaustive scans was artificial. In other words self-termination might take the form of a tendency to end the search after a match has been obtained although termination need not immediately follow the match (Klatzky, Juola & Atkinson, 1971).

To account for the probability of occurrence, repetition effect and serial position effects, Sternberg (1975) has suggested three possible modifications of his model. First, the time needed to form an internal representation of the test stimulus in the encoding stage might depend on how frequently or recently that stimulus had been presented. This would be able to account for the effects of trial sequence and stimulus probability.

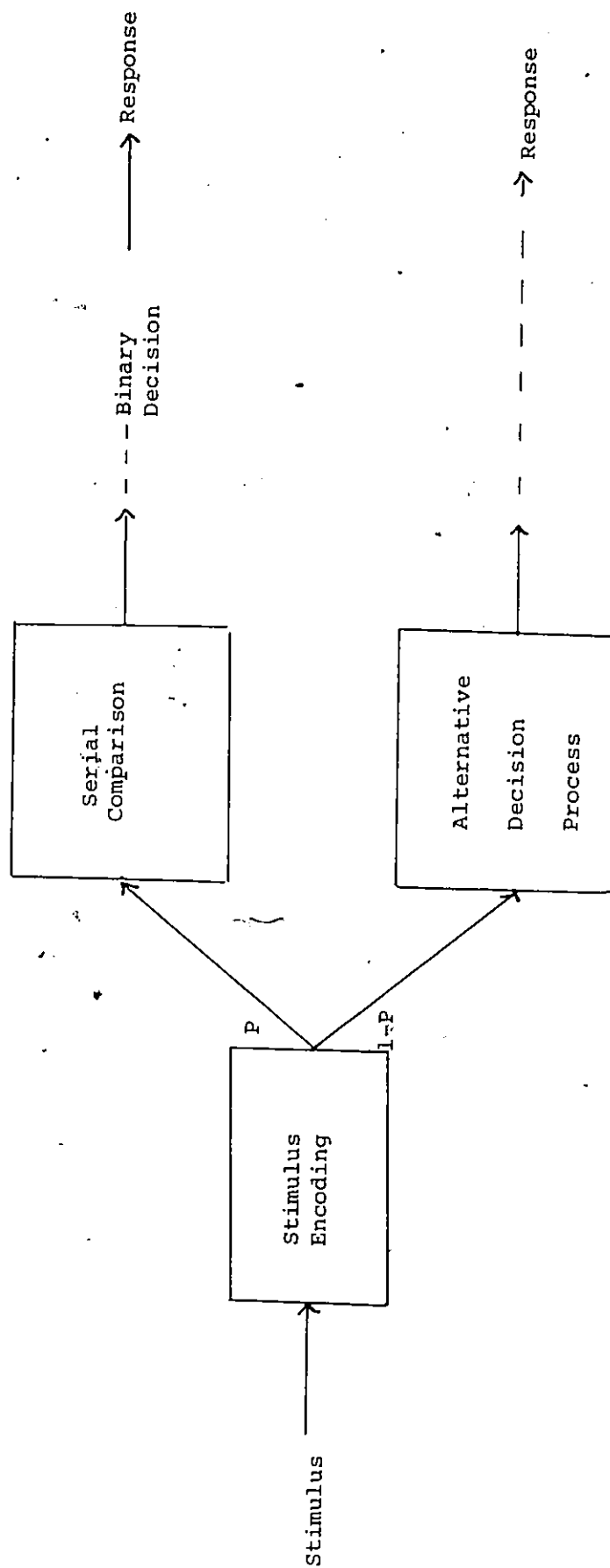


FIGURE 2: Modification of Sternberg's Model (Sternberg, 1975)

A second modification suggested that when an item that appeared twice in the positive set was tested and two matches occurred, the strength of the internal signal was increased indicating a match. Sternberg suggested that this would account for the repetition effect. Finally, to explain the varying reaction time with probability of occurrence of positive set items, a probabilistic mixture of serial comparison processes was proposed (Figure 2). On the basis of an early analysis of the stimulus a branch occurred so that the serial comparison process was executed on a proportion, P , of the trials and an alternative process on the remaining trials. For example, in a fixed-set procedure, the test stimulus could have first been compared to a representation of the previous stimulus. If they matched, the previous response would be repeated and if not, the positive set would be scanned.

Theios' Model

As a result of the difficulties encountered in Sternberg's model, Theios (1975) proposed a new model which involved a self-terminating search rather than a serial exhaustive search. This model assumed that the encoded representations of all the elements of the set of possible stimuli were stored in either short- or long-term memory, along with the codes of their respective responses as paired associates (Theios, Smith, Hayiland, Traupmann & Moy, 1973). The short-term part of memory was conceived as a dynamic stack or heirarchy in which representations of the set of possible stimuli were changing positions from trial to trial, but were probabilistically ordered on the basis of recency and frequency of occurrence. The representations of the more recent and more frequent stimuli were more likely to be located at or near the top of the memory stack. Infrequent and non-recent stimuli

were more likely to have their representations stored further down in the memory stack. If the memory store was considered to be of limited capacity, then the infrequent and non-recent stimuli may not be represented in the memory stack, but must have their representations retrieved from long-term memory. The size of the short-term memory stack may have been variable and have been determined in part by instructions to the subject and the demands of the task. The difference with the Sternberg model was the assumption that both positive and negative stimuli may be represented in the memory stack, since the contents and ordering of the memory stack were determined by the sequence of stimulus events, trial by trial.

Theios (1975) began with the assumption that to differentially respond to a stimulus, a serial sequence of transformations of the stimulus information took place before a response emerged, see Figure 3.

<u>Information</u>	<u>Process</u>	<u>Time</u>
S	stimulation	
s	stimulus input	Ti
s-n	identification	Ts
n-r	response determination	Tr
r-p	response program selection	Tp
p-R	response output	To
R	response	

FIGURE 3: Theios' Model of Reaction Time

The overall response latency of response R to stimulus S was considered as a summation of the individual process times.

$$T_{SR} = T_i + T_s + T_r + T_p + T_o$$

The following text offered a brief description of the processes proposed by Theios (1975) -

Stimulus input time: The information in the form of physical stimulation (s) was input to the nervous system and transformed to a stimulus code (s) which could be used by memory. The input time, (T_i), was a decreasing function of stimulus intensity and duration. Thus, stimulus input time was the time it took to register or encode the information in the stimulus into the memory system in such a way that it was possible to identify the stimulus.

Stimulus identification time: In this process, the memory code (s) was used to identify the stimulus. The identification time, (T_s), yielded the name (n) of the stimulus. Theios suggested that the name code could be thought of as the name of the class of memory codes of which the stimulus code was a member. The name code may also be conceived as the location or address in memory where information about the stimulus was stored. After the identification process, the subject 'knew' what the stimulus was and was in a position to initiate a response. Identification time was inversely related to the clarity of the physical stimulus. Sternberg (1967) presented the subject with a degraded stimulus and suggested that the resulting increased reaction time was due to an increased time taken to identify (or categorize) a relatively ambiguous stimulus.

Stimulus ensemble size and stimulus presentation probabilities were found to have very little effect on identification time, but it should be noted that most of the experiments employed alphanumeric characters or digits (Theios, 1975). It also appeared that stimulus identification time

depended heavily upon the context in which the stimulus was presented. A shorter identification time was found when the stimulus differed greatly from the rest of the experimental ensemble (Fraisse, 1967).

Response determination time: After the stimulus was identified, the name code (n) could be used to determine the code (r) for the appropriate response. The time to determine the response code was T_r . If the response code (r) was maximally similar to the name code (as in reading or other highly practiced skills of high compatibility), then the response determination time was small and relatively independent of the number of stimulus-response alternatives and stimulus presentation probability. If the response code was not highly practiced or similar to the stimulus name code, then response determination took longer, and its finishing time increased with the number of stimulus-response alternatives and with decreases in the frequency of occurrence of the stimulus.

Theios (1975) suggested that the slope of the reaction time function reflected the relative position of the response in a hierarchy of response associated with the name code of the stimulus. If the response was the first one in the hierarchy (as in reading or other highly practiced responses), then the response would be fast and relatively independent of the number of other stimulus-response alternatives in the experimental ensemble. This would correspond to a zero slope. As the response moved further down in the hierarchy then the slope would gradually increase as the result of increasing response latency with increases in the number of other stimulus-response alternatives.

Several variables have been proposed that may affect response determination time (Theios, 1975). First, the amount of practice of the stimulus-response association was an obvious factor. The more well practiced associations would have correspondingly lower reaction times. Second, the fewer the possible responses to a stimulus, the faster the response determination time would be. This was perhaps why linguistic stimuli which have only one associated response, such as reading, result in shorter response latencies than non-linguistic stimuli. In the latter case, several responses may be associated with the stimulus, such as a picture, where each response would be valid in a given context.

Third, decreases in stimulus-response compatibility (or increases in the number of transformation that occur between stimulus and response) led to increases in both the slope and the intercept of the mean response latency as a function of the number of stimulus-response alternatives (Alluisi, Strain & Thrumond, 1964). Thus, compatibility also affected response determination time. A similar relationship existed for spatial-motor compatibility. Where there was a natural spatial mapping of stimuli to a motor response choice latencies were lower than if that relationship was made less compatible (Fitts & Seeger, 1953; Fitts & Deininger, 1954). The lower the spatial-motor compatibility, the larger the slope of the reaction time function. According to the response hierarchy notion, increased response latency in low compatibility tasks was the result of the response being low in the hierarchy, due to the lack of practice, competing responses, or a required sequence of response-code transformations.

Finally, if the required response was the first one in the response hierarchy of a stimulus code, then stimulus presentation probability should

have little effect on response latency. If the response was not dominant in the response hierarchy, the stimulus occurrence provided occasion for the response to move up the hierarchy, thus decreasing response determination time.

Response program selection time: After determining the cognitive response appropriate to the stimulus, a motor response has to be selected and performed. Sternberg (1969) showed a bias in response requirements in that response latency systematically decreased as response frequency increased. The following variables should result in a decreased response program selection time: a) extended practice, b) increases in response frequency, c) reduction in the number of different response alternatives.

Response program selection involved a transformation which was similar to that which occurred during response determination. In that process, the transformation from the name code of the stimulus to a decision about task-relevant class membership of the stimulus took place. In response program selection there was a transformation from the 'cognitive' response code to the actual motor response code.

Response output time: After the response output program had been selected, the overt response was executed. The response execution time was represented by T_o and was a function of the specific response involved and most probably would be a decreasing function of response practice. In most studies, it would be impossible to completely separate response output time from stimulus input and identification time. Thus, input, identification and output times were typically summed together and called the zero intercept of the reaction time function.

The separation of response determination process from response program selection process was based upon the results of the repetition effect studies (Bertelson, 1965; Rabbitt, 1968; Smith, Chase & Smith, 1973). They demonstrated distinct effects for stimulus and response repetitions as opposed to simple response repetition effects. In the present model, the response determination process was sensitive to repetition of a stimulus-response pair, whereas response output program selection was sensitive to response repetitions independent of the stimulus.

Clark (1978) also supported the contention that response programming was an independent stage from response selection. She first assumed that stimulus-response compatibility affected response determination, while response complexity affected response programming. By use of the Sternberg additive factor method, Clark demonstrated that these two factors had additive effects on reaction time and thus affected two different stages.

Much of the support for Theios' model was derived from its ability to account for serial position effects, probability effects and the repetition effect. The majority of the research was centered around the self-terminating search versus the exhaustive search of Sternberg. As a consequence relatively little work has been directed towards the other stages of the two models.

Sternberg (1975) has suggested two limitations of the Theios model. The model was limited in that it could not account in a natural way for findings from the more typical procedure where positive and negative set sizes were unequal. To make the model fit two assumptions were proposed: 1) positive stimuli were more likely than negative stimuli to move to the beginning of the stored list after being presented, 2) when positive set

size has 'S' members, searching the list beyond the position $S + 1$ contributed no additional time to the reaction time. Even with these assumptions the model appeared incapable of producing equal effects of positive set size on reaction times of positive and negative responses at the same time as it produced no effects of the negative set size.

Finally, the minimum of the reaction time distribution changed as set size was increased. For a self-terminating search process, the minimum must be invariant with set size for the reason that regardless of set size there was some probability that the first comparison would produce a match. However, the fact that the sample minimum had been found to increase systematically with set size suggested strongly that the true minimum reaction time did not have the required invariance property.

Derivation of Hypothesis

Both Sternberg's and Theios' models could be subdivided into processes dealing with stimulus encoding and identification, response selection, and response programming, (Figure 4). This division of the models was necessary to demonstrate which processes would be affected by practice of parts of the complete task. The task to be considered in this study was a two choice reaction time task. The stimuli (red or green lights) were associated with a motor response to either the right or left. Thus, the subject would be presented with a light stimulus which would have to be encoded and identified. Following this the appropriate response to either the right or the left would be selected. Finally, the movement required for the response would have to be programmed.

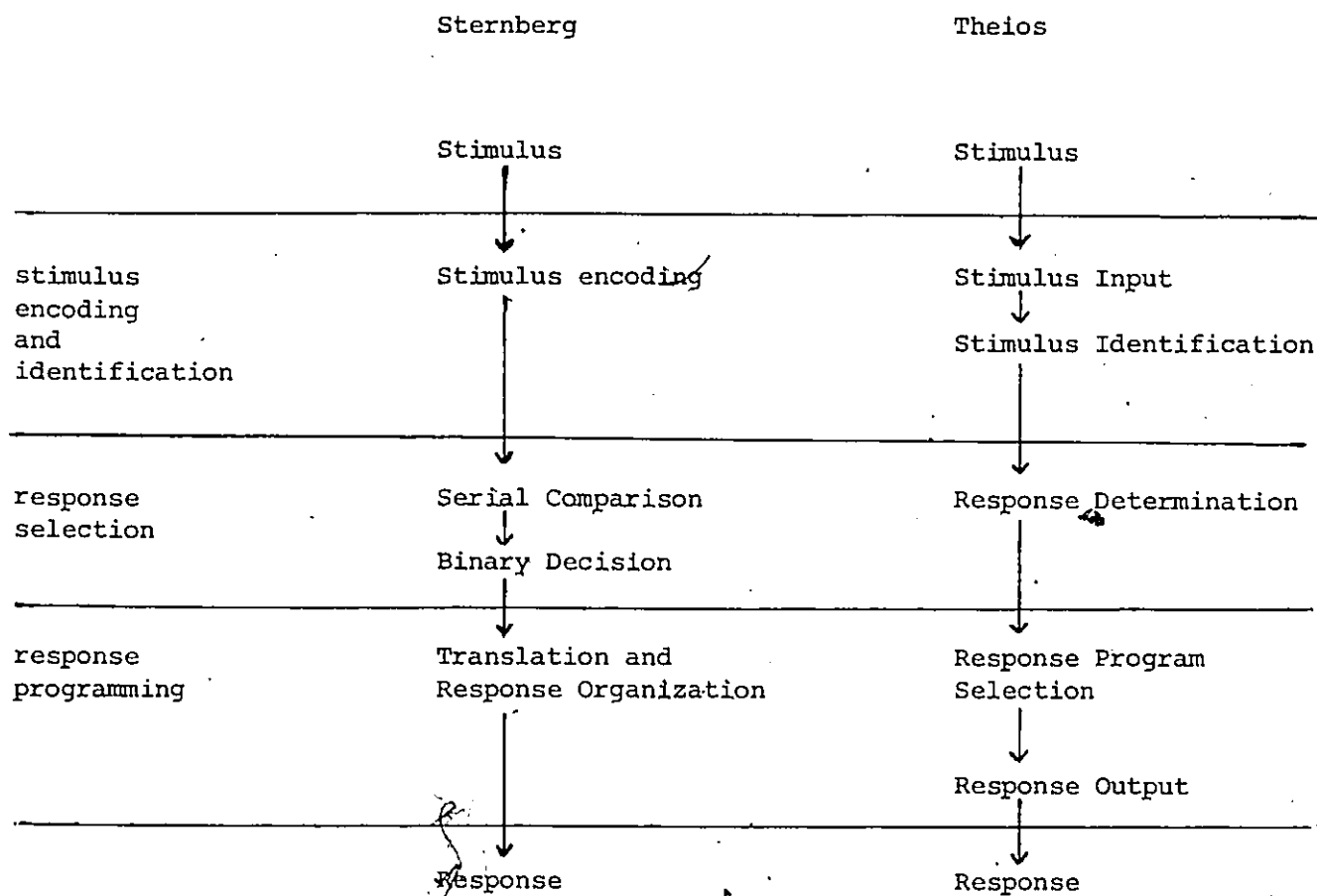


FIGURE 4: Stages of Sternberg's and Theios' Models

It was hypothesized, that by partitioning the task into two components, the underlying processes could be differentially affected. In the first condition the subject was presented with the stimuli and employed a simple ballistic motion to the corresponding right or left response keys. It was predicted that practice of this portion of the task would involve primarily stimulus encoding and identification, and response selection (i.e. selection of right or left response keys). There would of course be some response programming but this was kept at a minimum by using a simple ballistic motion. Because the information involved in stimulus encoding and identification, and response selection, was identical to that employed in the test trials, it was predicted that this practice would result in an increase in the efficiency of these processes. This increased efficiency would be reflected in a shortening of the reaction time.

The motor component of the task consisted of a complex movement which was also isolated for specific practice. In this condition the subjects were told to move to either the right or left, thereby, removing any response selection processes. The movements were self-initiated to further separate this condition from the reaction time paradigm. The subjects practiced simply the required motor movement to either the right or left response keys. It was hypothesized that this practice would involve only response programming processes and would result in an increased efficiency of the motor programs used for this task. This would also be reflected in a decrease of the reaction time as well as the movement time.

In summary, both types of practice should result in a shortening of the reaction time relative to a control group which had no practice. The relative decreases of the perceptual and motor practice conditions might also yield information regarding the effect of practice upon the subprocesses as well as their relative contributions to the reaction time.

A second purpose of the study was to consider the effect of information load on perceptual practice and of movement complexity on motor practice. It was proposed that these conditions would place extra stress on specific subprocesses thus causing them to increase their capacity. As a result, a simpler version of the same task would be processed more quickly with a consequently lower reaction time. The stimuli were kept the same but the information load was increased by the addition of white lights to the stimulus array. These extra white lights were not associated with the response. In the motor condition, a pause was inserted part way through the movement which acted to increase its complexity (Clark, 1978).

Although the main thrust of the study dealt with reaction time, movement time and movement time error were also included as dependent variables. This yields certain advantages. First, the use of a multivariate analysis incorporates the relationships among the dependent variables by taking their correlations into account and controls type one error.

Secondly, though the correlation between reaction time and movement time is low, the literature involving the effect of movement parameters on reaction time demonstrates a consistent relationship between movement and reaction time. The low correlation might be construed as evidence that the processes which occurred during reaction time were not the same as those which occurred during the movement phase. This does not imply, however, that there is no relationship between reaction time and movement time. Both Sternberg (1969) and Theios (1975) propose reaction time processes dealing with the selection and control of movement.

In practical terms, reference to a reaction time task usually includes a movement phase. Consequently, when discussing reaction time performance, an analysis of the total movement involved in the skill must also be made.

CHAPTER III

METHOD

Apparatus

The apparatus was diagramed in Figure 5. There were three response keys: the starting key and the right and left response keys. Between the starting key and the response keys was a conventional star tracer apparatus without the mirror. Directly behind the response keys was a display screen which contained a 6 x 6 light array (Figure 6). The screen contained four red, four green and twenty-eight white lights which were used during the cognitive practice and test trials. The lights were presented for a duration of 500 msec.

Three digital clocks were used to measure the following time intervals: reaction time (the time from the beginning of the presentation of the light stimulus until the subject's hand was raised off the starting key), movement time (the time from when the subject left the starting key until the subject depressed one of the response keys), movement time error (the time the subject was off the path on the star tracer).

The subject used a metal stylus to follow the star tracer path, which was held in the non-preferred hand at all times. The subject would begin at the junction between the two points directly in front of the starting key. Subjects would then follow the pattern to the right or to the left to the tip of the star nearest the respective response key.

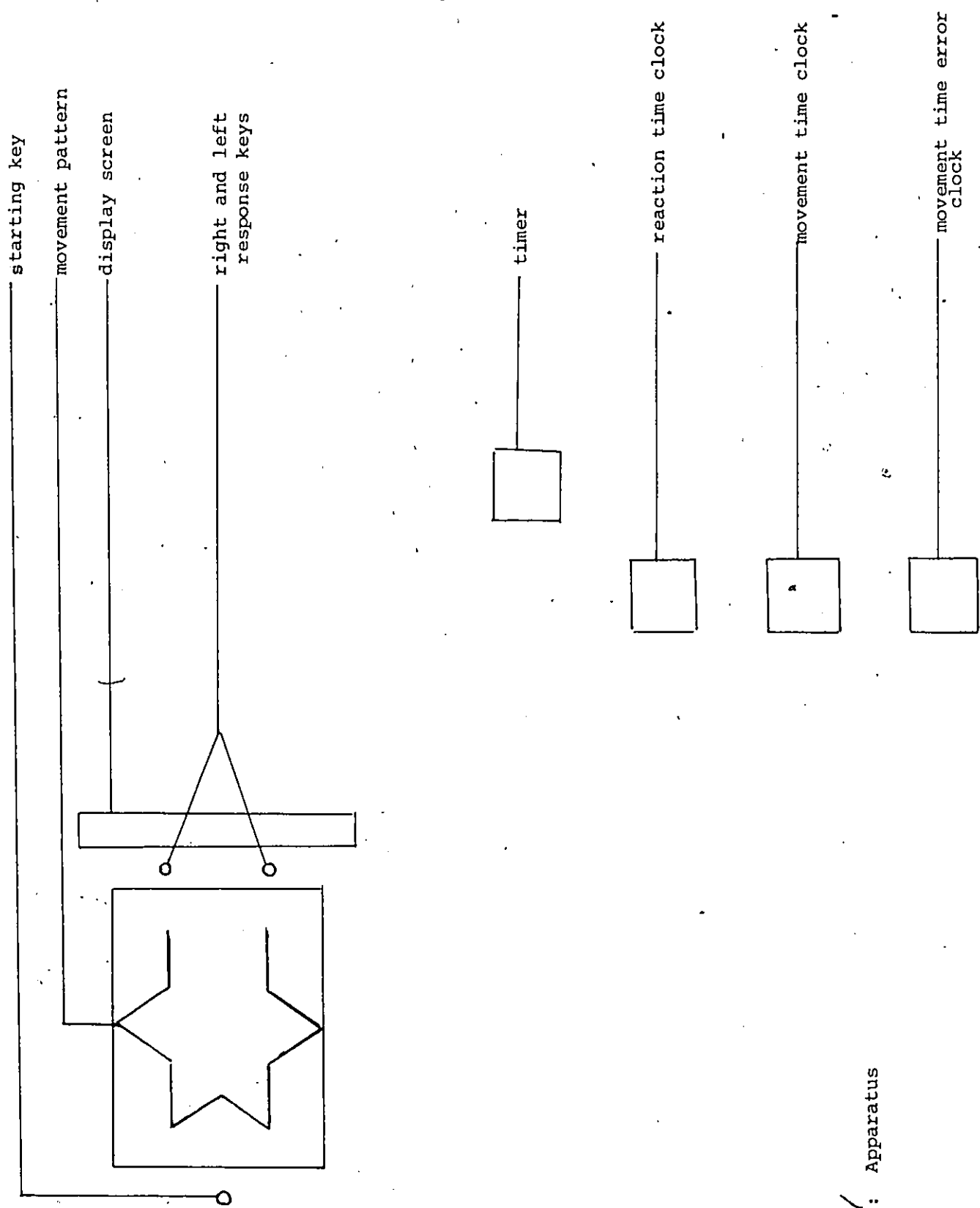


FIGURE 5: Apparatus

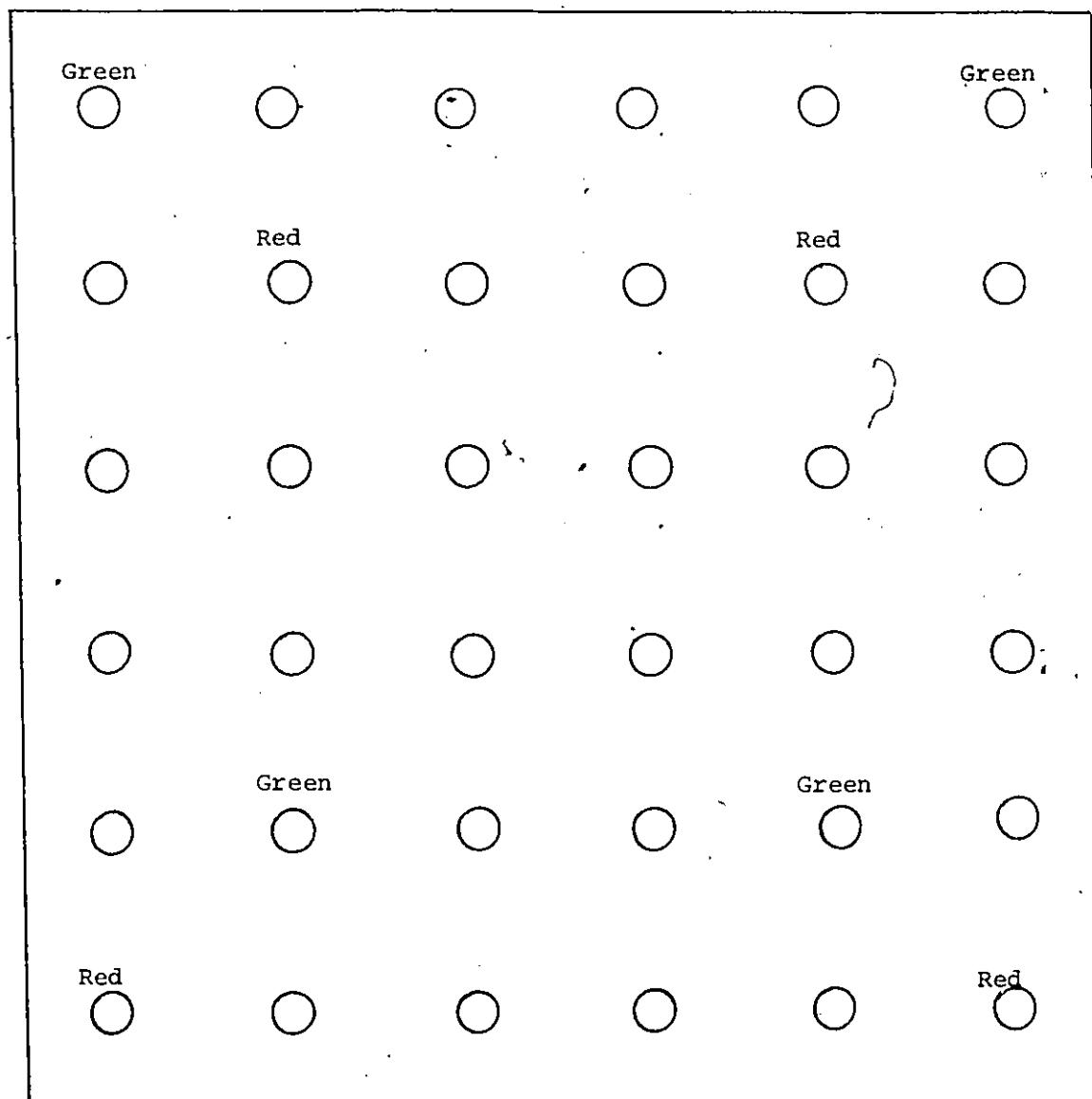


FIGURE 6: Display Screen

Subjects

Ninety-one subjects, both male and female, volunteered for the study and were randomly assigned to the five experimental conditions. Their ages range from fifteen to forty years with a mean age of twenty-three years.

Design

The design was a 5 x 2 multivariate design with repeated measures and three dependent variables. There were five groups in the experiment: control, perceptual practice, augmented perceptual practice, motor practice, and complex motor practice. Performance scores were averaged over trials 1 and 2 and trials 9 and 10 of the ten test trials to yield two repeated measures. The three dependent variables were reaction time, movement time and movement time error.

Procedure

The motor and perceptual practice groups had forty practice trials before the ten test trials. The control group had no practice trials and completed only the test trials. All subjects used their non-preferred hand and were tested individually. The test trials were identical for all subjects.

The perceptual practice group performed forty trials during which either a red or green light was presented in random order. The subject began by depressing the starting key with the non-preferred hand. When a red light was presented the subject reached forward as quickly as possible and pressed the right response key. Similarly, when a green light was presented the subject reached forward and pressed the left response key.

The augmented perceptual group followed an identical procedure with the addition that during the practice trials the information load was increased. This was accomplished by the addition of three randomly selected white lights on the 6 x 6 display screen.

The motor practice group also had forty practice trials during which, in a random sequence, they were told by the experimenter to follow the right hand or left hand side of the star pattern. The response was self-initiated by the subject so as to avoid any cognitive processes inherent in a reaction time response. The subjects were instructed to move as fast as possible but to remain on the star pattern. The complex motor practice group completed the motor practice trials with the movement increased in complexity. This was achieved by placing a target 10 cm to the right and left of the middle points of the star (Figure 7). The subjects were required to reach over with their non-preferred hand and touch the target when they reached the closest point of the star pattern. After touching the target, they would return to the pattern where they had left and continue. This manoeuvre created a pause in the movement which acted to increase the complexity (Clark, 1978).

During the practice trials for all groups, feedback was given at the end of each trial. For the perceptual practice groups, this consisted of their reaction time. The motor practice groups received their movement time and movement time error. During the practice trials all subjects were encouraged to improve their performance.

The ten test trials combined elements of both the motor and perceptual practice. The subject began by depressing the starting key with the non-preferred hand. When a red light was presented, the subject followed the

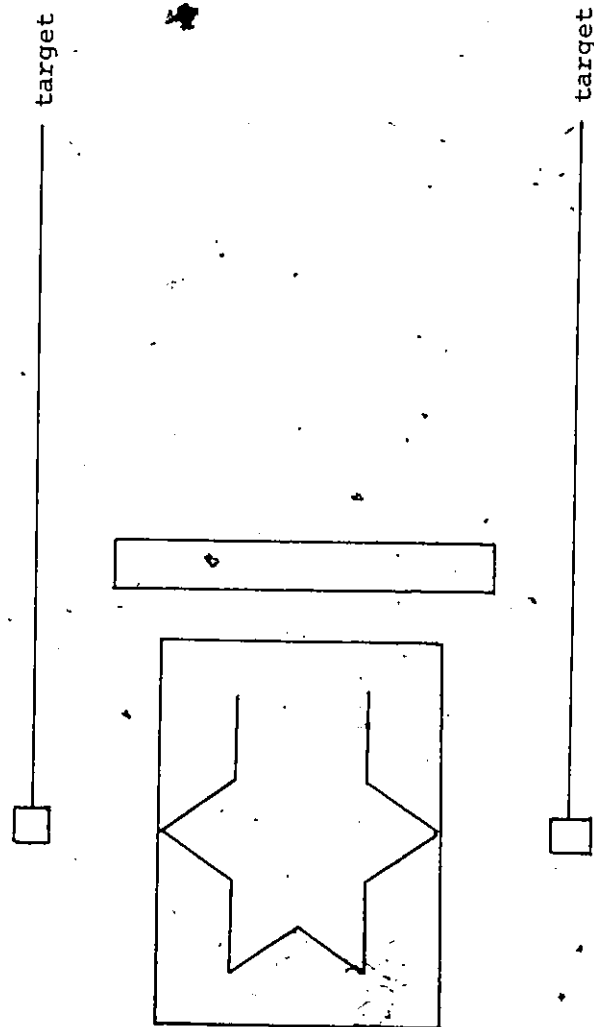


FIGURE 7: Modified Apparatus for Complex Motor Practice

right hand side of the star pattern and pressed the right response key. When a green light was presented the subject followed the left hand side of the star pattern and pressed the left response key. The green and red lights were presented in a random sequence and no feedback was given on any of the test trials.

Analysis of Data

The design and the number of dependent variables dictated the use of a Multivariate Analysis of Variance of the data. This was accomplished by the use of the Full Rank Multivariate Linear Model Computer Program, written by James E. Carlson, Faculty of Education, University of Ottawa.

Two post hoc procedures were used to describe the significant main effects. The first procedure involved the use of the error variances from the multivariate analysis of variance. This procedure yields the significant contrasts between the means within each dependent variable. However, it does not describe the relationships among the dependent variables relative to the main effects.

To achieve this second aim a discriminant analysis was performed. For this analysis Carlson's program was used.

A brief description of discriminant analysis follows. This analysis is based on the formation of a function relating several populations to the variables on which they were measured. The function is conditional on the maximum separation of the various populations, or group means, on the different dependent variables.

Cooper (1977) described the linear discriminant function as follows: If there were k well-defined populations whose subjects were

measured on p variables, $x_1, x_2, x_3, \dots, x_p$, a linear discriminant function Y would be the weighted composite,

$$Y = w_1 x_1 + w_2 x_2 + \dots + w_p x_p$$

where the weights w_i are such that the differences among the group Y -means are maximized.

When there are more than two groups, there may be a number of discriminant functions. Some of these functions may produce a significant separation among group means; some may not. The first linear discriminant function is determined by the largest eigen value. Each succeeding non-zero eigen value similarly determines a further linear discriminant function which is mutually uncorrelated (in the sample) with any other function so produced. Each successive function is determined so as to maximize the relative separation of the groups after the preceding functions have been partialled out (Cooper, 1977; Tatsuoka, 1971).

Whether or not a particular discriminant function produced a significant separation among the group Y -means could be tested by the means of a number of statistics. These included Roy's, Wilks, Lawley-Hottelling and Pillai Criteria and the appropriate Bartlett V statistic which was measured on a Chi Squared (χ^2) distribution (Cooper, 1977).

An indication of the relevance of the discriminant function may be demonstrated by the discriminatory power. This refers to the proportion of the total variability of the discriminant function which is attributable to group differences (Cooper, 1977), and is usually expressed as percent variance.

Discriminant analysis is not interpreted in the same manner as the analysis of variance statistics. A discriminant function that is statistically significant implies that the separation of the experimental groups on the discriminant dimension is significant. The dimension, represented by the function, is a composite of all the dependent variables used in the analysis. In geometric terms, the function would form a new dimension in an n -dimensional space, where each dimension corresponds to one of the n dependent variables. The spatial relationship between the discriminant dimension and the dependent variable dimensions is based on their correlations. A dependent variable, having a high correlation with the discriminant function, would have its dimension lying relatively close to the discriminant dimension. Thus, the group separations which were maximized on the discriminant dimension would be reflected to some degree (depending upon the correlation) on the dependent variable dimension.

CHAPTER IV

RESULTS

The design of the experiment was a 5×2 repeated measures design with three dependent variables. The data collected on trials one and two and trials nine and ten of the test trials was averaged to form the two repeated measures. In some cases the third or eighth trials respectively, were used in place of one of the other trials if there was a mechanical error or the subject was not attending to the stimulus array during the trial.

Two of the dependent variables were reaction time and movement time. The third dependent variable was a ratio of movement time error to movement time, expressed as a percentage. Movement time error was found to be dependent on movement speed. The greater the speed of movement, the smaller the movement time error, regardless of the extent of the error in terms of distance travelled off the star tracer path. The ratio of movement time error to movement time yielded an unbiased indication relative to movement speed of the accuracy of the movement.

The direction of the response, i.e. to the right or left, was also recorded to investigate errors that might have occurred in response selection. The number of errors which occurred during the test trials was negligible and no incorrect responses were recorded on the trials used in the analysis.

Six subjects were dropped from the study because their reaction time performance on three or more trials was extremely large. (See Appendix D for a frequency distribution of all the subjects for RTI scores.)

Carlson's 1979 Full Rank Multivariate Linear Model Program was

used to perform a multivariate analysis of variance on the data collected during the test trials. The first three dependent variables (RT1, MT1, MTE1/MT1) refer to the measurements averaged over test trials one and two. The second groups of variables (RT2, MT2, MTE2/MT2) refer to the data from test trials nine and ten.

All the main effects were significant to the .01 level of probability (Table 2) indicating there was a significant difference between the five experimental groups as well as across the repeated measures. There was also a significant interaction between the group effect and the repeated measures effect.

The post hoc procedure which used the error variances of the multivariate analysis of variance was computed for each of the main effects. Unfortunately, because of the size of the standard errors for the various contrasts, only one post hoc contrast was significant (Table 3). The contrast demonstrated that there was a significant difference between MT1 and MT2 for the control group.

A discriminant analysis which has been proposed by several authors (Tatsuoka, 1969, 1971, 1973; Huberty, 1975) as an alternate means for studying group separation was performed as a follow-up to a multivariate analysis of variances. An alternative procedure for the analysis of the RT1 data is presented in Appendix B.

Table 4 lists the statistics (Roy's Criteria and Bartlett's V Statistic) and the percent variance for each function calculated for the main effects. As can be seen, there were two functions yielding significant separations among the experimental groups. Only one function was found to be significant for differences between the repeated measures, and another one for the interaction between experimental groups and repeated measures.

TABLE 1

SUMMARY OF REACTION TIME, MOVEMENT TIME AND % MOVEMENT TIME ERROR MEANS

GROUP	RT1*	MT1*	MTE1/MT1	RT2	MT2	MTE2/MT2
Control	612	2641	26%	524	1885	33%
Perceptual	512	2536	26%	414	2128	30%
Augmented Perceptual	492	2964	21%	479	2545	25%
Motor	562	2406	20%	510	2477	19%
Complex Motor	528	2431	25%	447	2447	20%

* RT and MT expressed in milliseconds

TABLE 2

SUMMARY OF MULTIVARIATE ANALYSIS OF VARIANCE

SOURCE	CALCULATED VALUES		CRITICAL VALUES	
Groups	$\lambda(6, 4, 86)$	= .396*	$.01^U(6, 4, 80)$	= .578
	$\theta(4, .5, 39.5)$	= .434*	$.01^\theta(4, .5, 39.5)$	= .268
	$U^{(s)}(4, .5, 39.5)$	= 1.160*	$.01^{U^{(s)}}(4, .5, 40)$	= .562
	$V^{(s)}(4, .5, 39.5)$	= .759*	$.01^{V^{(s)}}(4, 15, 40)$	= .454
Repeated Measures	$\lambda(3, 5, 86)$	= .429*	$.01^U(3, 5, 80)$	= .684
	$\theta(3, .5, 41)$	= .491*	$.01^\theta(3, .5, 41)$	= .223
	$U^{(s)}(3, .5, 41)$	= 1.145*	$.01^{U^{(s)}}(3, .5, 40)$	= .400
	$V^{(s)}(3, .5, 41)$	= .651*	$.01^{V^{(s)}}(3, .5, 40)$	= .330
Interaction	$\lambda(3, 4, 86)$	= .655*	$.01^U(3, 4, 80)$	= .721
	$\theta(3, 0, 41)$	= .287*	$.01^\theta(3, 0, 41)$	= .203
	$U^{(s)}(3, 0, 41)$	= .490*	$.01^{U^{(s)}}(3, 0, 40)$	= .341
	$V^{(s)}(3, 0, 41)$	= .370*	$.01^{V^{(s)}}(3, 0, 40)$	= .286

Multivariate Statistics used:

Wilks' Lambda Criterion (λ)
 Roy's Largest Root Criterion (θ)
 Lawley - Hotelling Trace Criterion ($U^{(s)}$)
 Pillai's Trace Criterion ($V^{(s)}$)

Note: Wilks' Lambda Criterion must be less than the critical value to be significant whereas the other criteria must be greater than the critical value.

TABLE 3

POST HOC ANALYSIS
 USING ERROR VARIANCES FROM MULTIVARIATE ANALYSIS
 CONTRAST BETWEEN MT1 AND MT2 FOR CONTROL GROUP

CONTRAST	STANDARD ERROR	POST HOC CONSTANT	RANGE
377.68*	52.72	$\lambda = 6.647$	$\begin{matrix} + \\ - \end{matrix} 350.43$
		$\phi = 5.01$	$\begin{matrix} + \\ - \end{matrix} 264.13$
		$U^{(s)} = 5.97$	$\begin{matrix} + \\ - \end{matrix} 314.74$
		$V^{(s)} = 6.62$	$\begin{matrix} + \\ - \end{matrix} 349.01$

* $p < .01$

DISCRIMINANT ANALYSIS

SOURCE	FUNCTION	PERCENT VARIANCE	CALCULATED VALUE	CRITICAL VALUE
Groups	1	66.19	$\theta_{(4,.5,39.5)} = .434^*$ $V = 78.21^*$	$.01 \theta_{(4,.5,39.5)} = .268$ $.01 \chi^2_{(24)} = 42.98$
	2	23.73	$\theta_{(3,.5,39.5)} = .216^*$ $V = 30.07^*$	$.05 \theta_{(3,.5,39.5)} = .185$ $.05 \chi^2_{(15)} = 25.00$
	3	7.52	$\theta_{(2,.5,39.5)} = .08$ $V = 9.53$	$.05 \theta_{(2,.5,39.5)} = .140$ $.05 \chi^2_{(8)} = 15.51$
	1	84.17	$\theta_{(3,.5,41)} = .491^*$ $V = 73.11^*$	$.01 \theta_{(3,.5,41)} = .223$ $.01 \chi^2_{(15)} = 30.58$
	2	13.38	$\theta_{(2,.5,41)} = .133$ $V = 14.72$	$.05 \theta_{(2,.5,41)} = .138$ $.05 \chi^2_{(8)} = 15.51$
	1	82.34	$\theta_{(3,0,41)} = .287^*$ $V = 36.41^*$	$.01 \theta_{(3,0,41)} = .203$ $.01 \chi^2_{(12)} = 26.22$
Interaction	2	12.10	$\theta_{(2,0,41)} = .056$ $V = 7.26$	$.05 \theta_{(2,0,41)} = .120$ $.05 \chi^2_{(6)} = 12.59$

Statistics Used:

Roy's Criterion (θ)Bartlett's V Statistic (V)

TABLE 5

CORRELATIONS BETWEEN DEPENDENT VARIABLES AND
THE DISCRIMINANT FUNCTIONS

SOURCE	FUNCTION	VARIABLE	CORRELATION
Groups	1	RT1	.275
		MT1	.098
		MTE1 / MT1	.196
		RT2	.136
		MT2	.440
		MTE2 / MT2	.547
	2	RT1	-.615
		MT1	.302
		MTE1 / MT1	-.016
		RT2	.422
		MT2	.208
		MTE2 / MT2	.157

TABLE 6

CORRELATIONS BETWEEN DEPENDENT VARIABLES AND
THE DISCRIMINANT FUNCTIONS

SOURCE	FUNCTION	VARIABLE	CORRELATION
Repeated Measures	1	RT	.517
		MT	.886
		MTE / MT	.365
Interaction	1	RT	-.106
		MT	-.991
		MTE / MT	.561

To determine the "relative importance" of the various discriminant variables in a function, the correlation between each variable and the function was used (Cooper, 1977; Tatsuoka, 1971, 1973); see Tables 5 & 6. Correlations that ranged in absolute value between .4 and .7 were considered to represent a moderate amount of relationship. Therefore, even though a correlation in this range might be the largest contributor to the discriminant function, the other variables in the function must also be considered as contributors to the significant group separation. Correlations of .8 or .9, absolute value, signify a high amount of relationship with the discriminant function whereas those below .3 absolute value reflect a low amount of relationship.

The first function that distinguished among the experimental groups was primarily a "movement dimension". This was suggested because the largest correlations were from MT2 (-.440) and MTE2/MT2 (.547). The largest contributor to the dimension was the movement error term. Figures 9 and 10 show graphically the large separations between the experimental groups on test trials 9 and 10 for MT2 and MTE2/MT2. The sign of the correlation shows the direction of the relationship. In this case as the numerical value of MTE2/MT2 increased so did the numerical value of the discriminant function. MT2 decreased as values of the discriminant function increased.

The second function could be interpreted as primarily a "reaction time" dimension. The major contributors to this function were RT1 and RT2 with moderate correlations of -.615 and -.422, respectively.

The function related to maximum group separation across the repeated measures had one strong and one moderate contributor. MT with a correlation of .886 was the largest contributor, and RT with a correlation

of .517 was a secondary contributor. It was mainly these two variables which distinguished among the experiment groups from the beginning to the end of the test trials. The final discriminant function was related to the interaction effect. The major contributor to the interaction was MT with a correlation of -.991. An interaction was also present in the MTE/MT data which had a correlation of .561 (Figure 9, 10).

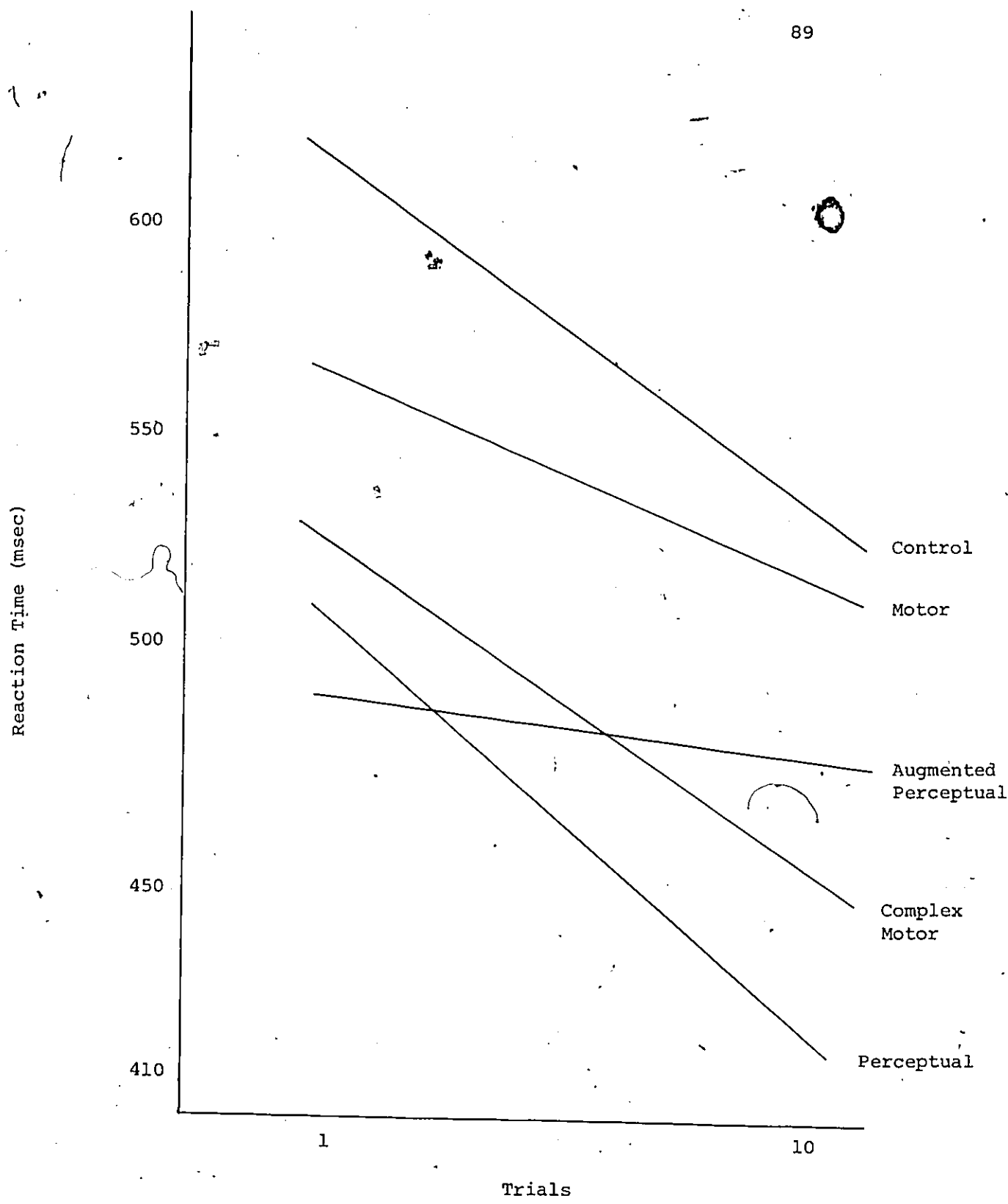


FIGURE 8: Reaction Time Across Test Trials

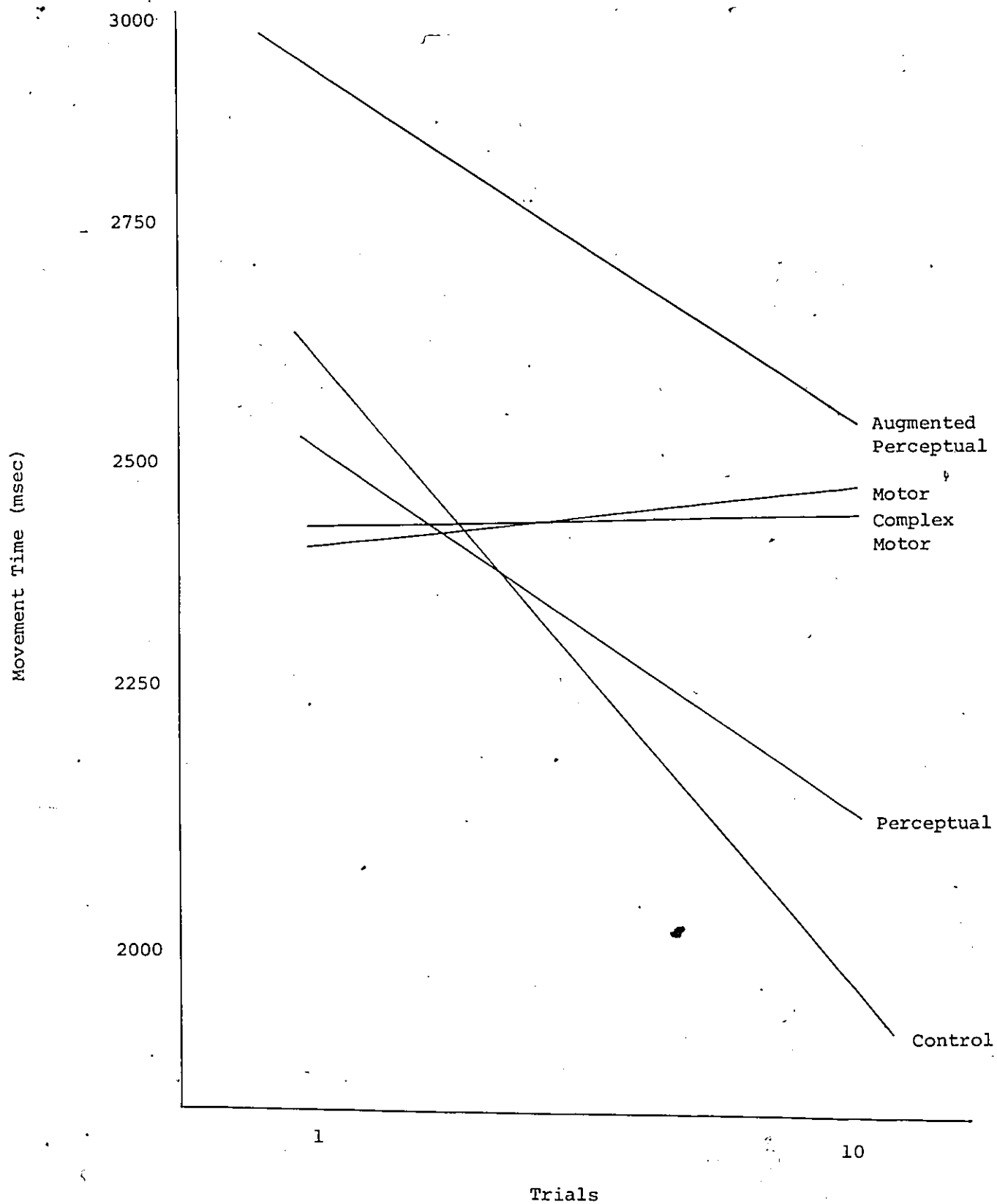


FIGURE 9: Movement Time Across Test Trials

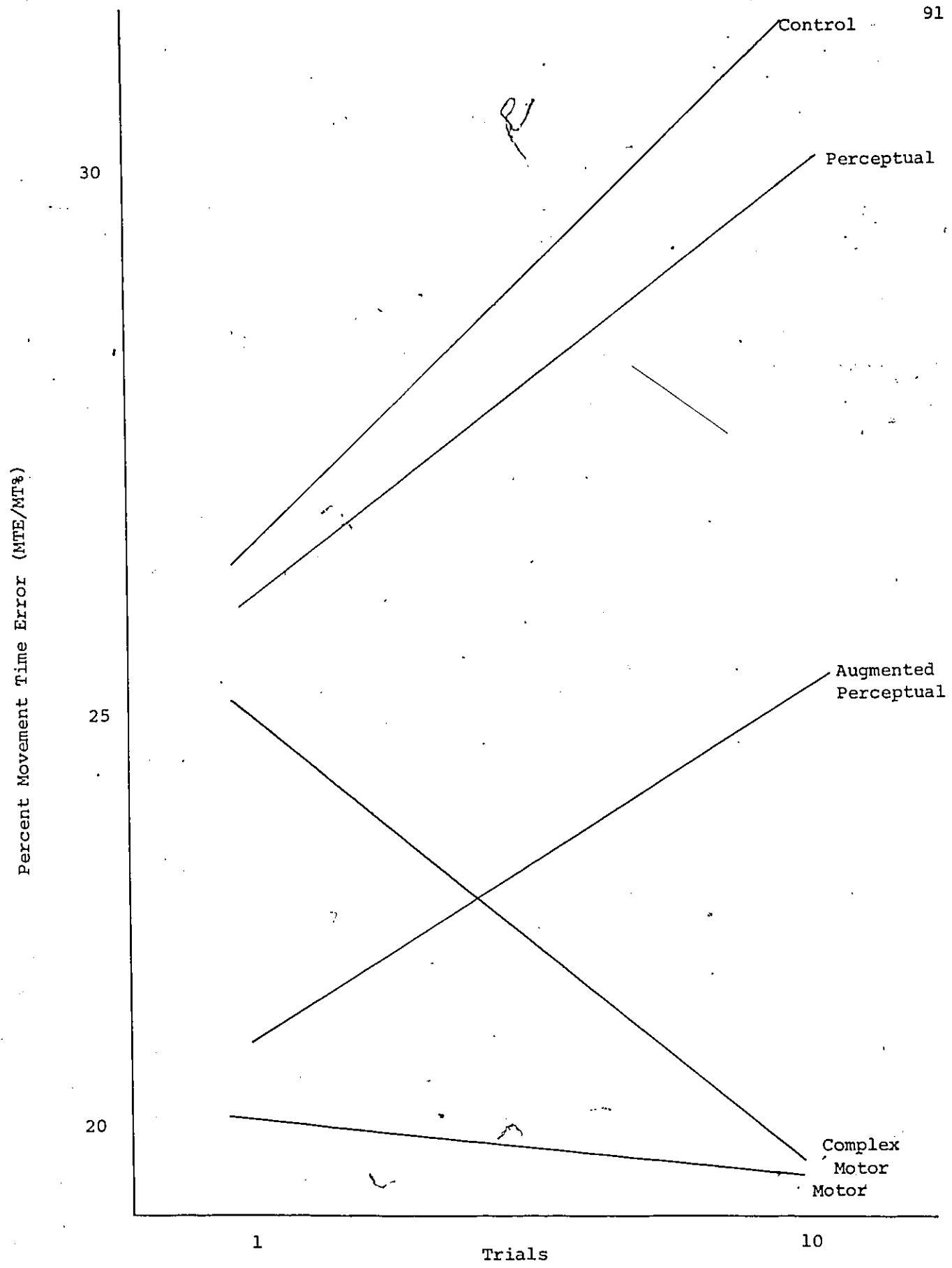


FIGURE 10: % Movement Time Error Across Test Trials

DISCUSSION

The three hypotheses proposed in the study were as follows:

- 1) Specific practice of either perceptual or motor components of the experimental task results in a decreased reaction time relative to a control group which experienced neither type of practice.
- 2) Increases in information load or movement complexity during practice of the perceptual or motor portions of the task, respectively, results in a decreased reaction time relative to a control group without practice and to the groups practicing the original perceptual or motor portions of the task.
- 3) Motor and complex motor practice results in a decreased movement time and movement time error relative to the no practice and perceptual groups.

It should be noted that both the hypotheses stated in the introduction referred to the performance on the first two test trials. No hypotheses were stated regarding performance during the test trials since the effect of the pre-test trial practice regimen would have been confounded by a practice effect from the test trials themselves.

Both of the hypotheses were supported by the results of the study. The reaction times averaged across the first two test trials (see Table 1) contributed to the separation of the experimental groups along the second discriminant dimension. Of major importance was the relative effect of practice on the reaction times of the experimental groups. The control group had the longest reaction time. The augmented perceptual group reacted faster than the perceptual group and both of the perceptual groups had

lower reaction times than both of the motor groups. The complex motor group had a faster reaction time than the motor group.

Theios' model was used to isolate the locus of the practice effect, Table 7 was designed to show the relation between Theios' model and the practice regimen of the various experimental groups. The processes proposed by Theios to occur during the reaction time interval were stimulus input, stimulus identification, response determination, response program selection, and response output. Theios suggested that the processes were sequential in time. The possibility that there was an overlap between the processes was considered, but the subsequent increase in complexity of the model limited its usefulness to this study.

The type of subprocesses thought to occur in each of Theios' time intervals was classified as either physiological or cognitive. Cognitive operation referred to a process which was psychological in origin and usually occurred in memory or some other cognitive space. Physiological processes referred to the processes involved in the reception of stimuli (in this case visual reception), the passage of electrical impulses throughout the nervous system and the initiation of muscle contraction.

The nature of the physiological processes and the cognitive operations can then be specified (Table 7). The physiological processes were understandably general since any effect of practice could not be accurately isolated within these processes. The cognitive operations were derived from Theios' model and consisted mainly of various transformations of information in memory.

The remainder of Table 7 describes the experimental task in relation to Theios' notation (Figure 3) of the subprocesses that occur in each time interval. In the first stage the light stimulation was translated

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Table 8

Processes Affected by Specific Practice

Theios' Model	Stimulus Input Time	Stimulus Identification Time	Response Determination Time	Response Program Selection Time	Response Output Time
Control	no practice	no practice	no practice	no practice	no practice
Perceptual Practice	practice	practice	practice	no practice	no practice
Augmented Perceptual Practice	practice under increased information load	practice	practice	no practice	no practice
Motor Practice	no practice	no practice	no practice	practice	practice
Complex Motor Practice	no practice	no practice	no practice	practice	practice complex movement

into a memory code corresponding to the different colours. The second stage resulted in the identification of the colours as red, green or white. The third stage associated a colour (red or green) with a response to the right or left. The response program selection transformed the 'right' or 'left' into a specific movement program to either the right or left. In the final stage, response output, the actual movement program was initiated.

The partitioning of the experimental task was necessary in order to demonstrate which portions of the task were practiced by the different experimental groups. The specific practice, experienced by each group could be directly related to the processes proposed by Theios (1975). Table 18 shows the relationship between Theios' processes and the practice regimens of the experimental groups. The control group had no pre-test practice, and thus had no previous practice of the reaction time processes before the test trials. The perceptual group practiced stimulus recognition and the association with the right or left response. Therefore, the decreased reaction time relative to the control group must be due to increased efficiency in the first three processes. The augmented perceptual practice group also experienced practice of the first three processes. The first two processes, though, were practiced under increased information load. The capacity of these processes was increased by the necessity of processing the white lights added to the stimulus array. Since only red or green lights were associated with a response, increased information load did not extend into the third stage. It would seem that increased information load increased the efficiency of the first two stages, and resulted in the lower reaction time of the augmented perceptual group

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Perceptual Practice	practice	practice	practice	no practice	no practice
Augmented Perceptual Practice	practice under increased information load	practice	practice	no practice	no practice
Motor Practice	no practice	no practice	no practice	practice	practice
Complex Motor Practice	no practice	no practice	no practice	practice	practice complex movement

relative to the perceptual practice group.

The motor group practiced the association of 'right' or 'left' (verbalized by the experimenter) with a movement pattern to the right or left. This practice encompassed the last two stages and also resulted in a lower reaction time relative to the control group. The complex motor practice group also associated 'right' or 'left' with the corresponding movement pattern, but performed a more complex movement. The increased movement complexity would affect only the last stage since it did not alter the association between 'right' and 'left' and the response initiated. The lower reaction time of the complex motor group suggested that increased complexity increased the efficiency of the final stage, response output.

The first two stages and the fifth stage involved both physiological and cognitive processes (Table 7). In order to isolate the locus of the practice effect these processes must be examined. In the first stage, stimulus input, the physiological process consisted of visual perception. The diameter of the visual column is approximately .5 mm (Guyton, 1972) which consists of both optic nerves. The speed of impulse transmission is directly proportional to the size of the fiber (Guyton, 1971). For the visual column, the impulses travel in excess of 120 m/sec (Ruch et al, 1965). If this speed was an indication of the durations of the other components of the visual system, then it could be concluded that the total duration must be relatively short. Combined with the fact that the stimulus, in terms of visual processing, was relatively simple, the practice effect, if any, would be relatively small and would be achieved fairly quickly. Because the total duration of this process would be relatively small, it was doubtful if a practice effect would be reflected in the experimental

observations. Therefore, it would appear that increased information load during practice would effect primarily the cognitive operations involved in stimulus input and stimulus identification, and not the physiological processes.

In the fifth stage, response output, the physiological processes involved motor neuron transmission and muscle contraction initiation. Fractionation of reaction time studies have demonstrated that motor time (the time from the initiation of a muscle action potential until the first observable movement) has a relatively constant duration of 38 to 42 msec (Botwinick & Thompson, 1966), and is relatively uninfluenced by factors that affect central processing. More specifically, Moris (1976) reported that motor time did not vary with extended practice. The motor time interval did not include the transmission of impulses along the motor neurons. The speed of impulse transmission in muscle nerves ranges from 80 to 100 m/sec depending upon the nerve diameter (Rush et al, 1965), which supports the supposition that motor time would not be greatly increased by the time taken for motor impulse transmission. With a speed of 80 m/sec and a distance of 1 m, it would take a nerve impulse 12.5 msec to travel the distance. Therefore, it would appear that the locus of the practice effect of more complex movements lay in the cognitive operations of motor program initiation, and not the physiological processes.

Movement time and movement time error on test trials one and two were not large contributors to the movement dimension. Movement time (MT1) though did contribute to the reaction time function (function 2) with a correlation of .302. Although the contribution was not large, it was seen that it distinguished the two motor practice groups - which had lower movement times - from the other three groups. Overall, it would seem that perceptual practice initially benefitted only reaction time, whereas motor

practice initially benefited both reaction time and movement time.

The remainder of the results dealt with performance over the ten test trials. It should be noted that any effects of the pre-test practice regimen were confounded by practice effects of the test trials themselves. Since all groups experienced the same amount of practice on the test trials, these results might have indicated how the test trial practice was affected by the pre-test practice.

The largest contributor to the differences between the repeated measures was movement time (correlation .886) which showed the largest decreases across the test trials. This was further substantiated by the fact that MT2 was also a large contributor to the separation of the experimental groups (function 1). Movement time, however, must be considered relative to movement accuracy. MTE2/MT2 was also a major contributor to group differences, which showed that those groups which experienced large decreases in movement time across the test trials (control, perceptual and augmented perceptual groups) also exhibited large increases in error. The two motor groups which did not show any large change in movement time, decreased their movement time error. It would appear that motor practice benefited the movement time and accuracy over the test trials, whereas perceptual practice or no practice did not benefit motor performance. The above explanation also accounted for the large interaction of which movement time and movement time error were the largest contributors.

Reaction time also contributed to the repeated measures function (correlation .517). All groups decreased in reaction time and, except for the performance of the augmented perceptual group, they retained the

same relationship that they exhibited at the beginning of the test trials. It was unknown whether the performance of the augmented perceptual group was due to an inhibitory effect of increased information load during the practice phases or another effect not known to the experimenter.

In summary, a choice reaction time task can be divided into two distinct components: a perceptual component and a motor component. Similarly, the processes which occur during the reaction time interval can be subdivided into those processes related to the perceptual component and those related to the motor component (Theios, 1975). It was reasoned that practice of the perceptual or motor components, in isolation from the rest of the perceptual-motor task, would differentially affect those processes related to the two components relative to a no practice control group.

The results of this study demonstrated that previous perceptual or motor practice produced a decreased initial reaction time. It was shown that perceptual practice influenced the first three processes of Theios' model and motor practice, the remaining two. Within each process, physiological or cognitive processes were specified. It was shown how the physiological processes could not have accounted for the practice effect because their total duration was very small. Thus, it was reasoned that the focus of the practice effect must lie in the cognitive operations which occurred prior to movement initiation.

Excluding program initiation, the cognitive operations were composed of transformations of information whose relevance to the repetition effect, various probability effects, stimulus - response compatibility and the Hick-Hyman relationship has been previously shown (Theios, 1975). It

would now appear that the effect of various movement parameters would lie in the program initiation stage since they do not involve the transformation of information, but rather details of motor programming.

Indirectly this study has supported Theios' model in that it has shown that the underlying cognitive processes occurring during the reaction time interval could be differentially affected by means of specific practice. It further suggested that perceptual-motor tasks should be considered as a composite of perceptual and motor processes. In the past, this has been an unstated assumption but researchers have not gone to the next step of dividing the perceptual-motor task into its components and studying them separately.

In practical terms, several suggestions regarding reaction time could be made. Though nothing can replace practice of the actual task, practice and equipment restrictions have forced many coaches to consider alternatives. This study supported the contention that skills that involve reaction time could benefit from practice regimens that do not necessarily depend upon the sport environment. The first task of the coach would be to isolate those skills that depend to a great extent upon reaction time. Once this has been accomplished each skill should be divided into perceptual and motor portions. The perceptual portion would consist of the stimuli that the athlete must react to. The number of alternative stimuli, the clarity of the stimuli, the speed with which stimuli must be processed and the differentiation of irrelevant from relevant cues should be considered by the coach. Of major importance is the number of alternative stimuli since this has a direct linear relationship to reaction time. Reducing the stimuli to the fewest and most salient cues, could result in a reduced reaction time.

Following the above considerations, the recognition of the stimuli of concern to the athlete, could be practiced in isolation from the rest of the sport environment. One possible method of accomplishing this could be by taking slides of the various instances of occurrence of the stimuli. For example, in various team sports such as football or basketball, pictures of different plays or positions of players would be relevant to a player who was forced to make a pass. These slides could be presented to the player who could practice reacting to them. This would correspond to the perceptual practice condition of the study.

Similarly, the motor portion of the skill could also be practiced in isolation of the sport environment. The skill could also be practiced without being subjected to a reaction time condition. In this way, the athlete can concentrate upon the movement itself. More complex versions of the task could also be used to avoid boredom during practice.

CHAPTER VI

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

The purpose of this study was to determine the effect of specific practice of portions of a perceptual-motor task on the reaction time performance of the complete perceptual-motor task. A second purpose was to examine the effect of information load and movement complexity during practice on reaction time performance.

The hypotheses to be tested in this study were as follows:

- 1) Specific practice of either perceptual or motor components of the experimental task would result in a decreased reaction time relative to a control group which experienced neither type of practice.
- 2) Increases in information load or movement complexity during practice of the perceptual or motor portions of the task, respectively, would result in a decreased reaction time relative to a control group without practice and to the groups practicing the original perceptual or motor portions of the task.

Ninety-one subjects between the ages of fifteen and forty years volunteered to participate in the study. The subjects were randomly divided into five practice conditions and were tested on a two-choice reaction time task involving a complex motor response. The experimental groups received forty practice trials, followed by ten test trials.

The control group received no practice on the experimental task. The perceptual group practiced the stimulus recognition and response selection portions of the task. The augmented perceptual group practiced stimulus recognition and response selection under increased information load. The motor group practiced the motor response, while the complex motor group practiced a more complex version of the motor response.

The three dependent variables recorded on each test trial were reaction time, movement time and movement time error. The results of trials one and two and trials nine and ten were averaged to form two repeated measures. A 5 x 2 multivariate analysis of variance was performed to test the main effects. A discriminant analysis was used as a post hoc procedure.

Conclusions

In relation to the first hypothesis, it was found that:

1. Perceptual practice of a perceptual-motor task resulted in a decrease in the initial reaction time to the total perceptual-motor task.
2. Motor practice of a perceptual-motor task resulted in a decreased initial reaction time in the complete perceptual-motor task.

In relation to the second hypothesis, it was concluded:

1. Increased information load during perceptual practice further decreased the initial reaction time to the perceptual-motor task, by increasing the efficiency of the cognitive operations of stimulus input and identification.

2. Practice of a more complex version of the motor portion of the task resulted in a decreased initial reaction time relative to motor practice by increasing the efficiency of motor program initiation.

In relation to the third hypothesis it was concluded that:

1. Motor and complex motor practice resulted in a decreased movement time and movement time error on the first two test trials relative to the control and perceptual group.

Within the limitations of this study, the following conclusions could be made with respect to performance across the test trials:

1. Practice of the motor movement, or a complex version, resulted in an improvement of movement accuracy by decreasing percent movement time error while movement time remained relatively constant.
2. No practice or perceptual practice resulted in a decreased movement time but at the expense of an increased percent movement time error.
3. Perceptual practice of the task alone, or under conditions of increased information load or no practice, resulted in an increase in movement speed but with corresponding decreases in accuracy.
4. Practice of the total perceptual-motor task resulted in decreases in reaction time for all groups.

Recommendations

The review of literature indicated the diversity of research

related to reaction time. With the advent of the models of Sternberg and Theios, a unified perspective is gradually being formed. The primary thrust of current research should be involved with the clarification and validation of such models. In this way a cohesive model of reaction time, encompassing all areas of research may be formed.

The present study used two techniques not commonly found in reaction time research. The first involved the division of the perceptual-motor task into perceptual and motor components. The manipulation of the perceptual and motor portions of the task, relative to the complete task, appeared to be a fruitful method in the study of reaction time. This method enabled inferences to be made about the underlying cognitive operations. As a consequence, this method should be employed in future studies.

The second technique involved the use of three dependent variables in a multivariate analysis, as opposed to one dependent variable in a univariate analysis. This trend has already occurred in educational and psychological research, and now is just beginning in psychomotor research. The use of more than one dependent variable results in a stronger statistical test as well as yielding a clearer indication of overall performance.

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APPENDIX A

ESTIMATED VARIANCE - COVARIANCE MATRIX
FROM MULTIVARIATE ANALYSIS OF VARIANCE

APPENDIX A

ESTIMATED VARIANCE - COVARIANCE MATRIX

VARIATE	RT1	MT1	MTE1/MT1	RT2	MT2	MTE2/MT2
RT1	13173.76					
MT1	25096.97	776305.91				
MTE1/MT1	- 161.97	- 7798.43	1642.32			
RT2	5645.95	6862.38	- 9.05	13603.20		
MT2	22557.26	466278.92	-4895.89	8457.53	456469.56	
MTE2/MT2	- 198.16	- 5973.50	81.52	48.64	- 5807.52	138.44

APPENDIX B

ALTERNATE ANALYSIS OF RT1

APPENDIX B

ALTERNATE ANALYSIS OF RT1

The decision to use a multivariate analysis as opposed to a univariate analysis depended upon the relationship between the variables. If the variables measured the same process or were highly related to each other, a multivariate analysis would be appropriate. The degree of the relationship depends on:

- 1) the correlation between the variables and
- 2) the theoretical relationship between the variables.

The correlation between RT1 and MT1 was .20 which was a relatively low correlation. Reaction time and movement time, though, have a strong theoretical relationship as evidenced by the studies reviewed in movement parameters section. The processes that occur during the reaction time interval are not the same as those which occur during movement. The relationship exists in that the motor program is selected and initiated during the reaction time interval.

It was the author's decision to perform a multivariate analysis followed by a discriminant analysis. However, because the possibility existed that a univariate analysis might demonstrate a clearer indication of the experimental effects, a 5 x 2 analysis of variance with repeated measures was performed on reaction time using Carlson's 1979 program. Movement time and movement time error were not analyzed again because the strong relationship between them supported the appropriateness of a multivariate analysis.

The results of the univariate analysis supported the interpretation of the multivariate analysis of variance and the discriminant analysis. The contrasts of most relevance were those of RT1 which were significant except for the contrast between the control group and the motor group. The comparison of means of RT2 and between RT1 and RT2 are also reported and support the multivariate interpretation.

SUMMARY OF UNIVARIATE ANALYSIS

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F RATIO
Groups	282281	4	70570	3.7*
Error	1637820	86	19044	
Repeated Measures	185101	1	185101	23.9**
Interaction	38710	4	9677	.3
Error	666717	86	7752	

$$* .01 F(4, 60) = 3.65$$

$$** .01 F(1, 60) = 7.08$$

UNIVARIATE ANALYSIS: POST HOC RTI

GROUP	CONTRAST (MSEC)	SCHEFFE CONSTANT	RANGE
Control vs Perceptual	99.95*	78.17	178.12 to 21.78
Control vs Augmented Perceptual	119.92*		198.09 to 41.75
Control vs Motor	49.31		127.48 to -28.86
Control vs Complex Motor	83.44*		161.61 to 5.27

* $p < .01$

UNIVARIATE ANALYSIS; POST HOC RT2

GROUP	CONTRAST (MSEC)	SCHEFFE CONSTANT	RANGE
Control vs Perceptual	110.03*	78.17	188.20 to 31.86
Control vs Augmented Perceptual	45.0		123.17 to -33.17
Control vs Motor	13.78		91.95 to -64.39
Control vs Complex Motor	76.51**	65.08	141.59 to 11.43

* $p < .01$ ** $p < .05$

UNIVARIATE ANALYSIS: POST HOC RT1-RT2

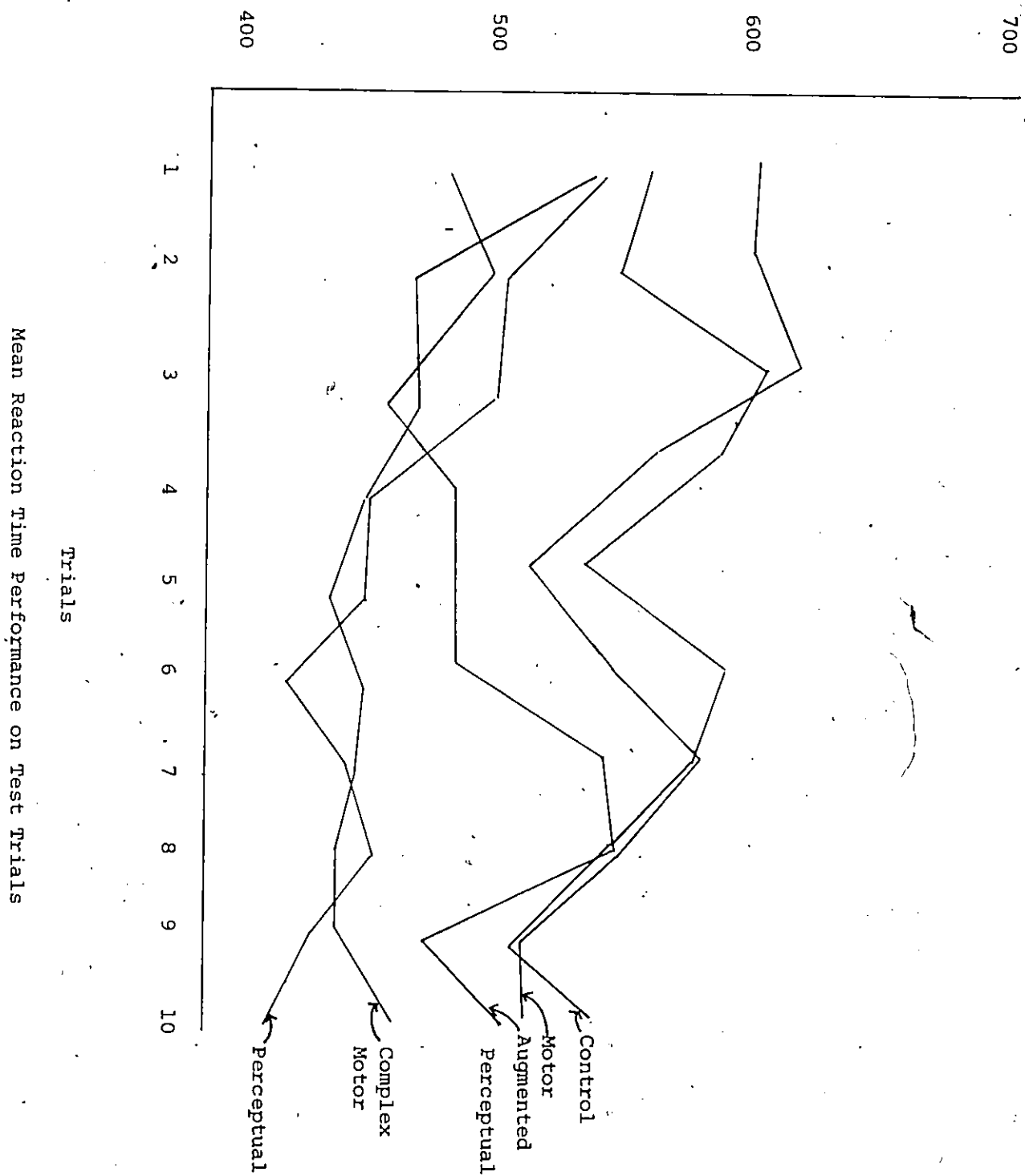
GROUP	CONTRAST (MSEC)	SCHEFFE CONSTANT	RANGE
Control	88*	34.7	122.7 to 53.3
Perceptual	98*		132.7 to 63.3
Augmented Perceptual	13		47.7 to -21.7
Motor	52*		86.7 to 17.3
Complex Motor	51*		115.7 to 46.3

* $p < .01$

APPENDIX C

MEAN REACTION TIME PERFORMANCE ON TEST TRIALS

MEAN PERFORMANCE SCORES



APPENDIX C

CONTROL GROUP

RT1	MT1	MTE1/MT1	RT2	MT2	MTE2/MT2
549.0	1348.0	43.2	335.0	1419.5	31.4
454.0	4037.0	11.1	455.5	2476.5	21.3
698.5	4049.0	15.5	436.0	2309.0	26.1
401.0	1756.0	35.5	501.5	1626.0	37.6
725.0	2537.0	17.4	400.5	1870.0	23.6
592.5	2213.5	38.5	399.5	2318.5	31.4
583.5	1713.0	43.2	583.0	1766.0	35.1
364.0	2379.5	29.1	302.0	1475.5	42.1
632.0	3239.5	30.8	402.5	1919.5	32.9
666.0	2812.5	10.9	468.0	2132.5	25.2
411.5	2370.5	16.8	449.5	1798.0	31.9
544.5	2047.0	33.1	367.5	1801.0	31.5
821.0	2487.0	29.5	487.0	2430.0	15.2
721.5	4289.5	7.7	563.0	1985.0	35.1
559.5	2730.5	12.8	390.0	1807.5	15.3
691.5	2900.5	26.4	536.0	1722.0	33.0
664.0	3043.5	24.9	578.5	1755.0	44.8
484.0	2305.0	28.2	389.0	2262.5	34.4
749.0	1517.0	38.8	828.5	1253.5	39.4
415.5	1993.5	33.1	793.0	1567.0	48.1
809.5	4846.5	6.4	648.0	1545.5	40.0
750.5	3172.0	28.9	698.0	2877.0	15.3
588.5	2990.0	16.00	411.5	1960.5	40.4
533.0	2258.0	43.9	572.5	1878.5	41.3
764.0	2533.0	33.0	731.0	1970.5	30.8
494.0	2064.5	26.8	617.5	1583.0	37.9
845.5	1664.0	30.7	798.0	1393.0	36.3

PERCEPTUAL GROUP

RT1	MT1	MTE1/MT1	RT2	MT2	MTE2/MT2
613.0	2501.0	12.3	448.0	2038.5	27.1
348.0	2060.0	18.9	422.0	1707.5	24.3
391.5	2738.0	26.9	408.5	2235.5	26.4
379.0	2285.5	31.5	345.0	1590.0	32.8
539.0	1838.0	26.5	378.0	1417.5	57.0
737.0	1868.5	31.0	290.0	2207.0	40.1
547.0	3800.5	9.6	413.0	3442.0	5.5
568.0	1954.5	43.2	526.5	1720.5	35.7
396.5	1792.5	29.5	361.5	1646.5	41.0
572.0	2832.5	32.3	591.0	2254.5	36.3
597.5	4874.5	10.3	448.0	3596.5	7.6
451.0	1890.5	37.9	333.5	1678.5	31.6

AUGMENTED PERCEPTUAL GROUP

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RT1	MT1	MTE1/MT1	RT2	MT2	MTE2/MT2
542.0	3033.5	23.1	472.5	1914.5	36.6
450.0	2203.5	41.4	423.5	1844.5	17.5
564.0	2822.5	19.2	537.5	2654.5	15.2
536.0	2445.0	27.3	621.5	1897.0	52.6
452.5	2075.0	34.1	569.5	1487.0	49.6
621.5	4511.0	12.7	495.5	4998.5	0.9
426.5	3040.0	2.8	327.5	2686.5	5.0
496.5	1511.0	36.2	543.0	1687.5	39.7
612.0	3752.0	12.4	638.0	3145.5	8.0
402.5	4291.0	22.4	449.5	2996.5	21.2
471.5	2208.5	29.5	251.5	1724.5	42.6
612.0	3392.0	5.4	559.5	3054.0	12.5
461.0	2567.5	30.4	323.5	2200.5	40.8
498.0	2696.5	9.7	622.5	3171.0	19.6
295.5	1991.0	26.9	308.0	1711.0	29.1
425.0	4876.5	1.2	517.5	3553.0	9.1

RT1	MT1	MTE1/MT1	RT2	MT2	MTE2/MT2
420.0	2895.0	5.4	410.0	2756.0	8.9
518.5	2931.0	16.3	321.0	2641.5	9.6
502.0	1914.0	31.2	473.0	1854.0	24.5
630.0	3102.0	13.0	411.5	2899.5	30.8
658.0	3585.0	7.3	527.5	3910.0	2.1
460.5	2033.0	22.3	348.0	1968.0	20.4
551.0	2636.0	30.9	472.0	2809.5	12.0
618.0	2448.0	24.2	511.5	2562.5	22.9
683.0	1286.0	53.4	606.0	2047.5	35.2
578.5	1682.5	22.5	665.0	1744.5	28.2
663.0	2029.0	25.5	382.0	1989.0	11.5
385.5	1761.0	17.1	443.5	1992.5	19.5
612.5	2189.0	8.8	522.0	2908.0	12.7
497.0	3269.5	19.8	501.5	2732.0	31.8
415.0	2915.5	19.8	496.0	2859.5	15.3
571.5	2494.5	13.9	544.0	2387.0	14.7
655.0	2760.0	21.2	596.0	2747.5	28.2
491.0	1473.0	25.1	653.5	1407.5	25.7
583.0	1633.0	32.9	557.5	1754.0	32.4
591.5	3073.0	4.2	644.0	3442.5	5.1
723.0	2418.0	9.7	624.5	2599.5	16.3

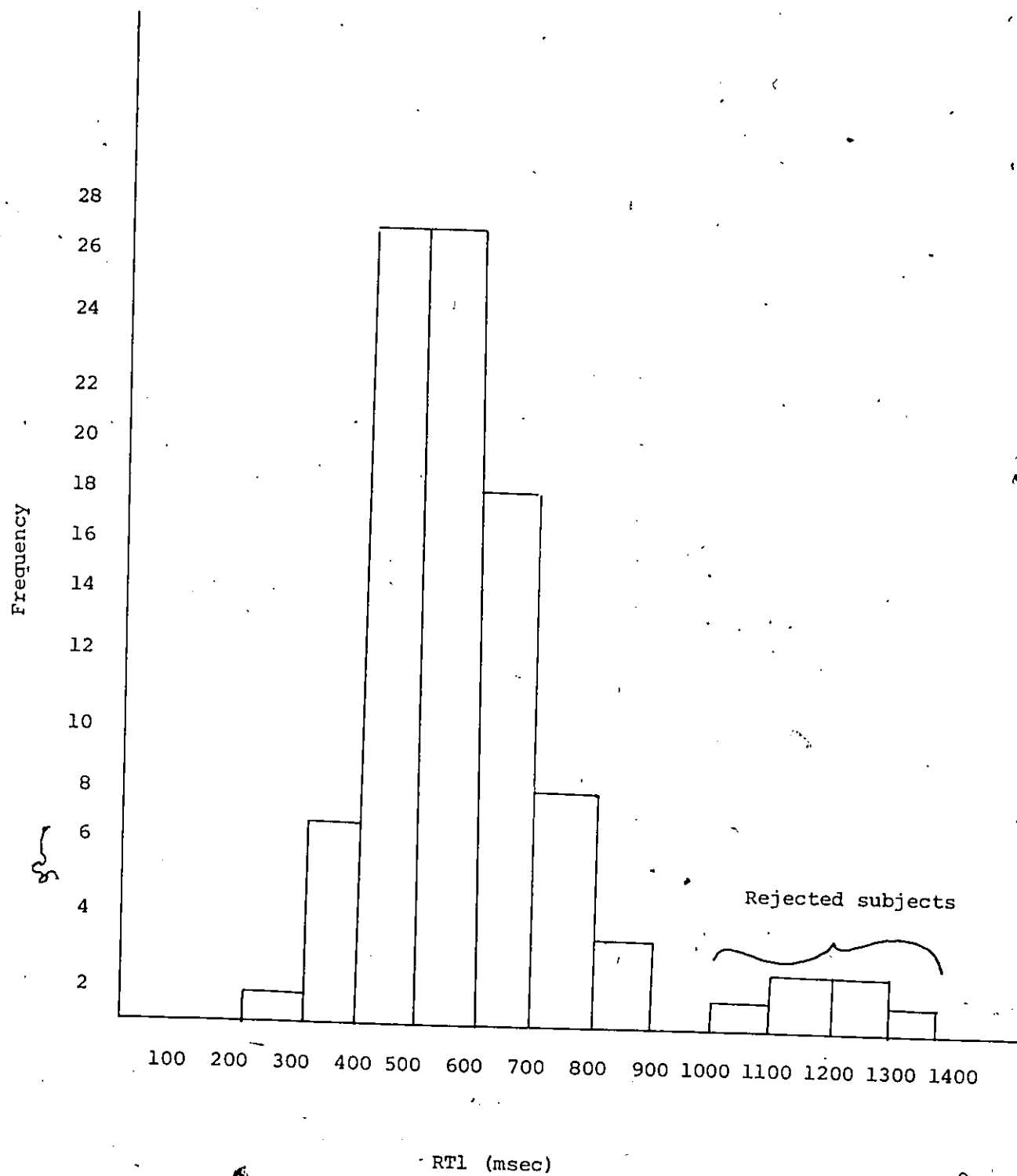
COMPLEX MOTOR GROUP

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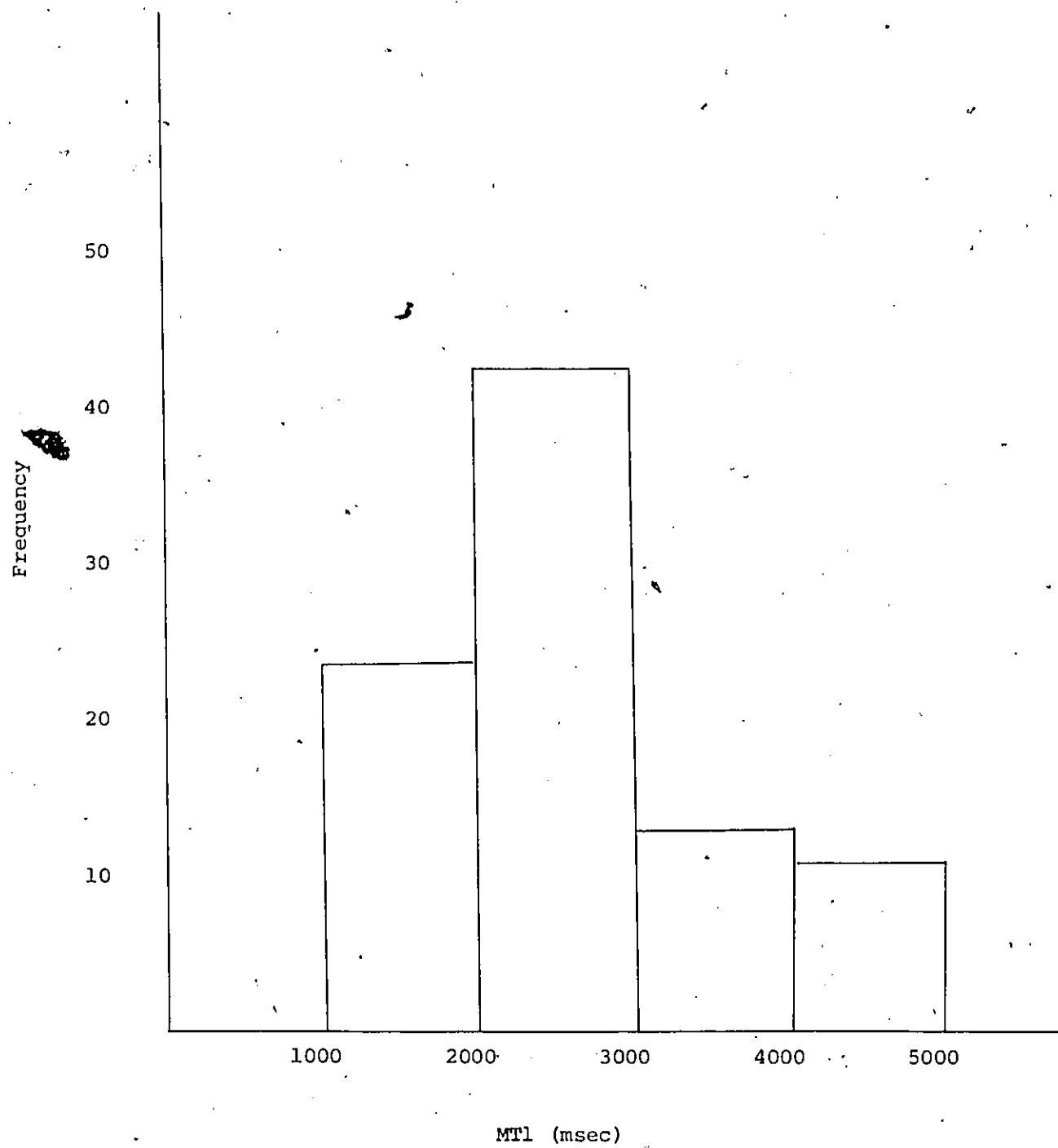
RT1	MT1	MTE1/MT1	RT2	MT2	MTE2/MT2
552.5	1431.0	41.5	318.5	1555.5	32.8
413.5	1165.0	42.2	368.5	1482.5	34.9
565.0	1170.5	44.9	406.5	1304.5	39.1
378.0	2262.5	36.3	401.0	2385.0	14.5
459.0	1885.5	19.1	431.5	2571.0	23.5
502.2	2185.5	14.3	321.0	2134.0	19.5
425.5	2134.5	20.8	477.5	2239.5	12.8
567.5	2302.0	40.7	467.0	2486.5	20.9
665.0	1748.0	32.8	604.0	1816.5	24.3
788.5	4150.0	8.4	525.0	3957.5	1.1
423.0	3082.5	14.4	465.0	2706.5	13.7
589.5	2114.0	28.0	486.5	2329.0	11.6
669.5	4337.5	5.5	577.5	4307.5	11.9
458.0	4030.5	5.2	426.5	3011.5	5.2
465.0	2463.5	16.8	433.0	2410.5	28.0

APPENDIX D

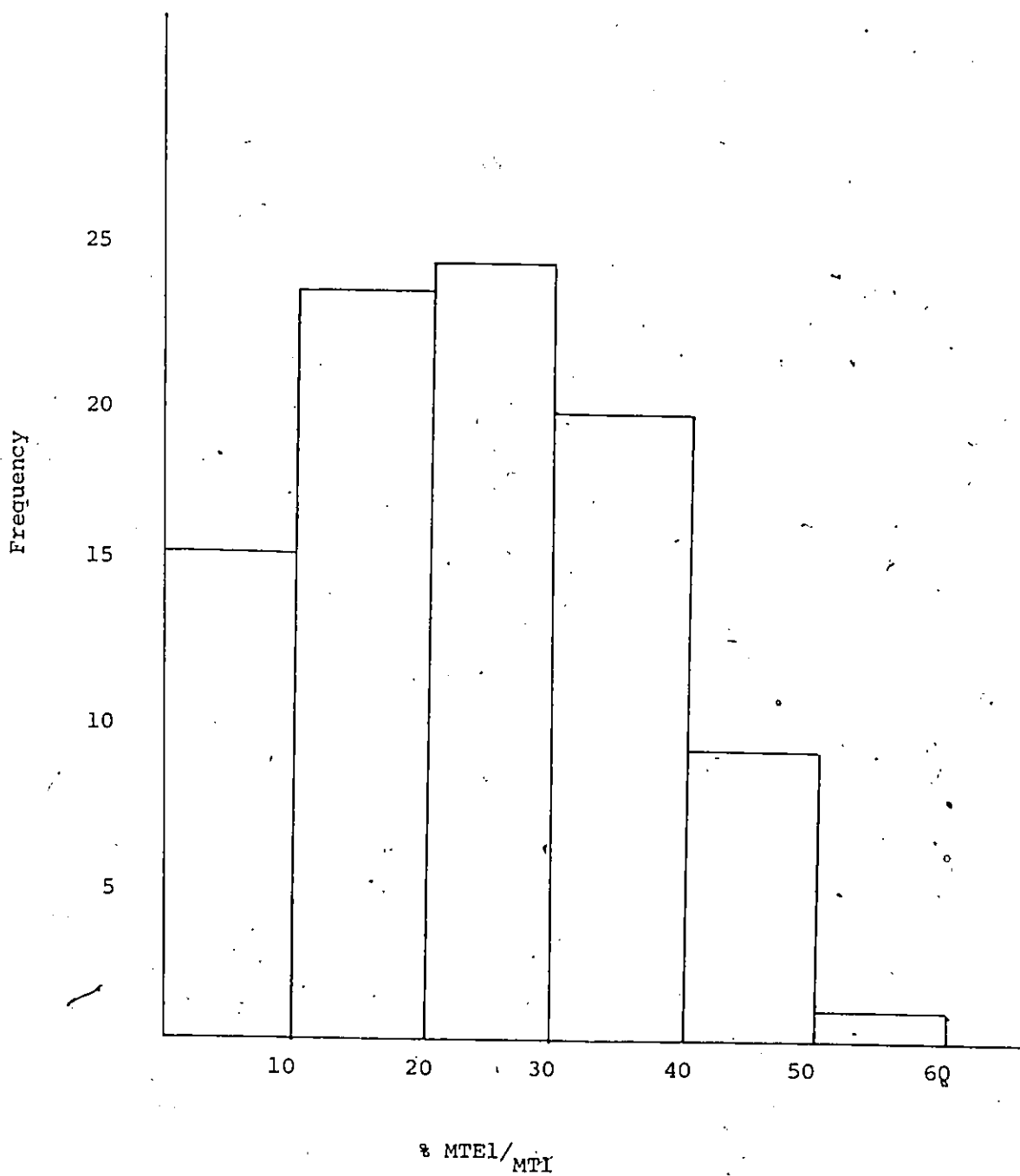
FREQUENCY DISTRIBUTIONS OF RT1, MT1, MTE1/MT1



Frequency Distribution of Subject Population



Frequency Distribution of Subject Population



Frequency Distribution of Subject Population

ABSTRACT

The purpose of this study was to determine the effect of practicing the perceptual or motor portions of a two choice reaction time task, involving a complex motor movement, on response latency to the complete task.

Ninety-one subjects were randomly divided into five experimental conditions. The control group received no practice and performed only the ten test trials. The other four groups performed forty practice trials before completing the ten test trials. The perceptual group practiced recognition of the stimulus and its association to a right or left response key. The augmented perceptual group experienced similar practice but under a condition of increased information load, by the addition of irrelevant lights to the stimulus array. The motor group performed the motor response on the practice trials. The complex motor group practiced a more complex version of the motor response.

A 5 x 2 multivariate analysis of variance with two repeated measures and three dependent variables was performed on the data. The test trial performance on trials one and two and trials nine and ten was averaged to form the two repeated measures. Reaction time, movement time and percent movement time error were the three dependent variables. A discriminant analysis was used as a post hoc procedure.

The results indicated that both perceptual and motor practice independently produced shorter reaction times than the no practice control group. Increased information load during perceptual practice and complex motor practice also resulted in reaction times less than the control group.

Motor practice resulted in a lower initial movement time than the perceptual or no practice conditions. Over the ten test trials the motor practice groups increased their accuracy by decreasing the percent movement time error. The control and perceptual groups also decreased their movement time but increased their percept movement time error.

The findings were discussed in relation to the processes proposed to occur during the reaction time interval by Theios (1975).