COMPARATIVE EFFECTS OF FORE PERIOD SIZE ON REACTION TIME OF SINGLE MOTOR UNIT DISCHARGES AND GROSS FINGER MOVEMENTS

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Emmett Brawner Swint, Jr.

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Approved:

M. Carr Payne, Chairman

E. Jo Baker

William D. McLeod

Date approved by Chairman: 8/23/74

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

SUMMARY

A single motor unit (SMU) has been defined as a "single motor-neuron and all the muscle fibers that it innervates." Monitoring muscle activity with surface electrodes and utilizing biofeedback procedures, subjects (Ss) voluntarily controlled motor units, providing a response which is normally beneath the S's conscious level of awareness.

Reaction time (RT) and accuracy of SMU discharges were examined under conditions of varying fore periods (FPs) of 2, 5, and 10 seconds, and SMU responses compared with gross finger movements (GMRs). RTs were examined according to (1) size of immediate FP, (2) size of preceding FP, and (3) relative size of preceding FP to immediate FP.

Six Ss produced accurate SMU discharges on 63 per cent of trials in the last two sessions. Examination of GMR RTs showed that immediate FP size was a major influence in RT but not in SMU responses. Preceding FP size and interaction of preceding FP to immediate FP size did not influence GMR or SMU RTs.

Variables which may have led to conflicting results of SMU responses when compared to other SMU RT studies and to gross measures of RT are discussed. Such variables may include: (1) type of monitoring electrodes, (2) degree of response control, (3) subject population, and (4) high RT variability between Ss and across sessions.

CHAPTER I

INTRODUCTION

Motor responses usually are defined operationally by the occurrence of some relatively large environmental event, e. g., pressing a key, activating a voice key, or maneuvering a hand or foot control (Bahrick & Noble, 1966). In certain situations these responses may have the disadvantage of being confined to a specific location on the organism (Sutton & Kimm, 1970) or of failing to measure low level muscle activity initiated long before detection of the gross response (Davis, 1959). Attempts to quantify this low level muscle activity often have utilized integrated measures of the electromyogram (EMG). These attempts, however, are limited by the specific recording methods and techniques selected. As a result, interpretation and comparison of different EMG findings have been difficult (Close, 1964; Basmajian, 1967b; Green, Walters, Green, & Murphy, 1969; Kahn, Bloodworth, & Woods, 1971).

Single Motor Unit Responses

Because of the problems associated with interpretation of different EMG findings, the single motor unit (SMU) discharge has been proposed to study low level motor activity (Basmajian, 1967b; Kahn, et al.,

1971). A SMU consists of a single motorneuron centrally located in gray matter of the spinal cord together with all muscle fibers that it activates (Liddell & Sherrington, 1925). When a motorneuron discharges, a muscular electrophysical event is produced (as a result of near simultaneous discharge of all muscle fibers synapsed to that motorneuron) that has a characteristic waveform, amplitude and duration (Basmajian, 1967a; Bucthal, 1960; Close, 1964). Detection of activity by electrodes placed in or over the muscle provides a means whereby SMU discharges can be monitored or utilized as responses.

Research in the field of voluntary control over SMU discharges has led to several observations. Normally, control over an isolated SMU discharge is beyond a subject's (S's) ability because it is not within his level of conscious awareness (Basmajian, 1963). Biofeedback methods in which amplified muscle activity is returned to S via visual and/or auditory channels have enabled S to control SMU discharges selectively while suppressing other SMU discharges within pick-up range of the electrodes.

SMU Discharge Characteristics

Certain characteristics of SMU discharges make them useful as responses in research on motor activity:

(1) having a specific waveform, constant amplitude, and constant duration enables reliable detection of response occurrence (Buchthal,

1960; Buchthal, Guld, & Rosenfalck, 1957a);

(2) being an all-or-none response and having a one-to-one relationship with motorneuron discharges provides a more precise pinpointing of time in which a response is initiated (Kahn, et al., 1971);

(3) being the smallest functional unit of muscle activity (Eccles & Sherrington, 1930), SMU recording retains information (changes in response frequency) that often is lost in integrative EMG measures (Close, 1964); and

(4) being present at response levels below S's awareness increases the sensitivity of measures and extends the range of measurable behavior to include covert responses (Close, 1964; Basmajian, 1967a; Green, et al., 1969; Kahn, et al., 1971; Hefferline, 1964).

SMU recording also has some limitations. At high levels of muscle activity (especially when SMU activity is recorded with surface electrodes), the tendency of SMU discharges to summate decreases the distinctiveness of waveforms (Close, 1964; Basmajian, 1967b; Grossman & Weiner, 1966). Furthermore, if a voluntary SMU response is desired, special training procedures are required for S to learn to activate a selected SMU.

Present SMU Research

Research involving SMU responses is beginning to fall into two categories:

(1) S has muscle activity monitored so as to describe some complex motor act, such as efficient learning of a musical or athletic skill (Basmajian, 1972) or to correlate with other obtained measures, e.g., degrees of tension as inferred from dynamometer readings (Kirkpatrick, 1972) and measures of personality, emotions, mental activity or unconscious behavior (Jacobson, 1930, 1931; Hefferline, 1962; Hefferline, Bruno, & Davidowitz, 1971; Hefferline & Perera, 1963; Budzynski, Stoyva, & Adler, 1970; Kahn, Swint, & Bowne, 1972); and

(2) S is required to attain voluntary control over SMU firings as a prerequisite to its use as a response. The latter category requires that training procedures utilizing externalized feedback be incorporated. Applications of SMU research using this procedure have included assessing the effects of drugs (Sutton & Kimm, 1970) and external stimulation, e.g., temperature (Wolf, 1973) on fine motor performance; the shaping of responses to control external devices such as stepping motors in prosthetic devices for rehabilitation of amputees (Basmajian, 1972); the correlating of more precisely defined peripheral events to central events via evoked potentials (McLeod, private communication; Kahn, et al., 1972) and assessing simple reaction time (RT) of SMU discharges (Quigley, 1968; Kimm, 1969; Sutton & Kimm, 1969, 1970; Thysell, 1969).

Simple RT and SMU Discharges

This thesis pursues the second line of research by examining further simple RT of SMU discharges. RT is a classical method that has been used to infer complexity of central processes from amount of time required for S to react to a presented stimulus (Woodworth & Schlosberg, 1954; Teichner, 1954).

One interest in RT studies has involved isolating those variables that alter S's expectancy for stimulus occurrence. Two such variables identified by Klemmer (1956) include: (1) S's time-keeping ability and (2) response signal variability within a set of RT trials. By providing S with a ready signal that precedes the response stimulus and by varying fore period (FP) size (time interval between the ready signal and response stimulus), certain systematic changes in RT latencies have been observed. A summary of these findings shows:

(1) RT is inversely proportional to the size of immediate FP, i.e., RT is longer on trials having short FPs and shorter on trials having long FPs (Telford, 1931; Klemmer, 1956; Karlin, 1959; Drazin, 1961);

(2) RT is not affected by absolute size of preceding FPs (Zahn, Rosenthal, & Shakow, 1963; Sanders, 1966); and

(3) RT is inversely proportional to size of preceding FP relative to immediate FP size, i.e., RT is longer on trials having a long FP preceded by a trial with a short FP and shorter on trials having a short

FP preceded by a trial with a long FP (Klemmer, 1956; Karlin, 1959; Zahn, et al., 1963). The difference in the second and third findings suggests that it is relative interaction of preceding FP size which affects RT. Selective findings from the literature on the effects of FP size on RT are reviewed in the next chapter.

Purpose of Thesis

This thesis proposes to investigate FP effects on SMU RT using surface electrode monitoring and to compare these effects with effects of a variable FP size on GMR RT. Three hypotheses will be tested when the response is a GMR and when the response is a SMU discharge:

Hypothesis One:

RT is inversely proportional to immediate FP size.

Hypothesis Two:

RT is not affected by absolute value of preceding FP size.

Hypothesis Three:

RT is inversely proportional to interaction between preceding FP and immediate FP size.

CHAPTER II

REVIEW OF LITERATURE

Introduction

The relevant literature covers two broad areas: simple RT studies and SMU studies. The simple RT studies relate primarily to the effects of FP size on RT of GMR responses. Those findings showing RT differences due to a varying FP are of particular importance.

The main focus of the selected literature on SMUs is the use of the SMU discharge in psychological procedures. This review includes studies leading to development of the concept of the SMU, some of the structural and functional properties of the SMU, and some of the procedures used in obtaining voluntary control over SMU discharges. Various methods used in assessing performance of voluntary SMU behavior and the variables found to affect SMU performance are cited.

The last portion of the review includes those studies in which the SMU response has been used in simple RT paradigms. Variables affecting SMU RT and effects of FP size on SMU RT are analyzed.

Simple Reaction Time

Organization of RT Research

Simple RT, time required for S to respond to a presented stimu-

lus with some predesignated response, has had a long history in psychology as a measure of a person's performance. Reviews of RT by Johnson (1923), Woodworth (1938), Woodworth & Schlosberg (1954), and Teichner (1954) are structured around three components: a sensory component, a central component, and a motor component. These reviews have pointed out how such variables as sensory modality involved, and how the intensity and duration of the stimulus and the onset and cessation of the stimulus may affect the sensory component of RT performance, and how the type of response required and function of responding member affect the motor component. Since sensory and motor components have been assessed by measuring the time for a signal to travel from a peripheral organ to some central component and from a central component to some responding member, differences in RTs have been attributed to complexity of information processed by central structures (Woodworth & Schlosberg, 1954). In the present review, central factors are discussed in terms of S's motivation, practice, fatigue, drug effects, and expectancy ("set") for the response signal. The last area, expectancy of the response signal, provides the focus of the review.

Expectancy and RT

The role of expectancy in RT studies is probably best understood in terms of the procedures used. Two signals normally are used in a RT study, a response signal and a ready signal. The response sig-

nal is a stimulus for S to respond with some predesignated response (e.g., a key press, finger movement, voice response, etc.). Among the variables associated with this signal that have been found to affect RT latencies are its intensity, duration, and the sensory mode involved (Teichner, 1954; Woodworth & Schlosberg, 1954). When a ready signal precedes the response signal, the interval between is designated as the fore period (FP). The purpose of the ready signal is primarily to give S some warning that the response signal is forthcoming so that he may prepare himself to respond. Recent research has shown that some parameters of the ready signal also affect RT performance. These parameters include its intensity (Behar & Adams, 1966; Karlin, 1959; Stilitz, 1972), its duration (Behar & Adams, 1966; Karlin, 1959), and sensory modality involved (Botwinick & Brinley, 1962). Moreover, interactive effects of ready signal intensity with response signal intensity have been reported by Stilitz (1972). The interactive effects of ready signal intensity and FP size are not as clear. Significant interactions were reported by Botwinick (1969) and Botwinick & Storandt (1972) but not by Behar & Adams (1966).

In RT studies of signal expectancy (Teichner, 1954; Klemmer, 1957; Sanders, 1966), the temporal relationship (FP) between ready signal and response signal has received more attention than other parameters. Two primary areas of research have included the search for an optimum FP size and effects of a varying FP on RT performance.

Optimum FP size. Studies of the temporal relationship between ready signal and response can be traced to the report of an optimum FP size of 2 secs by Woodrow (1914). Earlier, Breitwieser (1911) had found the optimum FP size to fall in a range of 1.0 to 4.0 secs but to differ for individual Ss. Teichner (1954) extended the range up to 8.0 secs.

Klemmer (1956) pointed out that an optimum FP size has meaning only when a homogeneous set of FPs are used, i.e., FP size remains constant for each trial in a set. In homogeneous sets, RTs have been shown to increase positively with an increase in FP size (Telford, 1931; Klemmer, 1956; Karlin, 1959; Drazin, 1961; Naatanen, 1963) because of S's imperfect time-keeping ability (Klemmer, 1956). Informational measures relating RT with time uncertainty have been given by Hick (1952), Klemmer (1957), and Thomas (1967, 1970). This relationship does not hold for small FPs; if FP size is made less than 0.5 sec, RTs do not continue to decrease. In this refractory period, a separate physiological process is thought to govern RT performance (Telford, 1931; Welford, 1952, 1959; Poulton, 1950; Davis, 1956; Klemmer, 1956).

Variability of FP sizes. A heterogeneous set of RT trials (produced by varying FP size in successive RT trials) reduces the number of anticipatory errors (S responds before the response signal is presented) because S cannot rely solely on his time-keeping ability to predict the occurrence of the response signal (Klemmer, 1956). Varying

FP size about some average value has the general effect of producing longer RTs than found in a homogeneous set having constant FPs of that value (Klemmer, 1956; Drazin, 1961; Naatanen, 1970). The difference in overall RTs becomes larger when the range of FP sizes in the heterogeneous set is increased (Klemmer, 1956; Karlin, 1959; Drazin, 1961; Naatanen, 1970) or when the average FP size about which the FPs vary is decreased (Klemmer, 1956; Drazin, 1961; Karlin, 1959).

A more important finding than the increase in RT is the nature of the relationship of RTs to FP size in heterogeneous sets. As noted in the preceding section, homogeneous sets produce longer RTs when FP size is increased. This finding does not hold in heterogeneous sets. Instead, shortest FPs yield the longest RTs while the longest FPs yield the shortest RTs (Klemmer, 1956, 1957; Karlin, 1959; Drazin, 1961; Telford, 1931; Teichner, 1954; Sanders, 1966; Naatanen, 1963, 1970; Zahn, et al., 1963).

In addition, the effect is more pronounced when the effects of the FP size of the immediately preceding trial are analyzed. The longest RTs result from a short FP preceded by a trial with a long FP while the shortest RTs result from a long FP preceded by a trial with a short FP (Klemmer, 1956, 1957; Karlin, 1959; Zahn, et al., 1963; Botwinick & Brinley, 1962; Sanders, 1966; Thomas, 1967).

For a heterogeneous set of RT trials, RT latency on a given trial is dependent on the FP size of that trial and on the relative FP

size of the preceding trial. A possible explanation for this interaction is that S adapts to the set of the preceding trial. For example, if a short FP is followed by a longer one, S will ready himself more quickly and maintain the readiness. As time passes, the probability that the signal will occur increases (Naatanen, 1970; Karlin, 1959). If a FP is long and a short FP follows, S will be "caught napping," resulting in a longer RT (Karlin, 1959). This "surprise effect" has been found to be particularly striking in certain populations thought to be deficient in ability to change sets quickly, e.g., schizophrenia (Cancro, Sutton, Kerr, & Sugerman, 1971; Huston, Shakow, & Riggs, 1937; Mowrer, 1941; Nideffer, et al., 1971; Rodnick & Shakow, 1940; Shakow, 1962; Wells & Kelley, 1922; Zahn & Rosenthal, 1965; Zahn, Rosenthal, & Shakow, 1961, 1963; Zahn, Shakow, & Rosenthal, 1961).

Recent evidence has shown that RT performance is also dependent on the manner in which FP sizes are distributed within a set of RT trials (Baumeister & Joubert, 1969; Mowbray, 1964; Stilitz, 1972; Naatanen, 1970; Zahn & Rosenthal, 1966; Requin & Granjon, 1969). All results that have been presented thus far are based on symmetrical distributions (each FP size appears an equal number of times in a set). By adding more trials having a certain FP size, S's expectation for a given FP size can be altered, producing changes in RT. However, the effects of these skewed distributions go beyond the extent of this study except that they give support to findings that S tends to adopt a "set"

which is in part determined by FP size of preceding trials.

Single Motor Unit (SMU) Response

Concept of SMU

Significant findings in the field of muscle physiology cited by Liddell & Sherrington (1925) that led them to the conceptualization of the SMU include: (1) Galvani's discovery in 1791 that muscles contract upon stimulation; (2) Bowditch's and Lucas's respective findings that this muscle contraction is all-or-none in heart and skeletal muscle; (3) Mines's conclusion that a stepwise muscular response is due to excitation of new nerve fibers which activates all muscle fibers supplied by them; (4) Piper's demonstration that an electromyogram represents action potentials generated during voluntary contraction of a muscle; and (5) Gasser and Newcomer's observation that action potentials from a muscle are fairly accurate copies of action potentials in a motor nerve fiber.

Sherrington (1929) described the SMU as "an individual motor nerve-fibre together with the bunch of muscle fibres it activates." Each SMU included a nerve cell centrally located in the gray matter of the spinal cord so that a group or "pool" of these cells represented the muscle in the spinal cord. Eccles & Sherrington (1930) argued that this arrangement was such that it could be considered a single functional entity.

Structural Properties of SMUs

Studies reviewed by Basmajian (1967b) and Harrison (1961) over a thirty-year period primarily attempted to describe the structural and functional characteristics of SMUs. These characteristics include: (1) number of muscle fibers innervated by a single motorneuron; (2) number of SMUs in a single muscle with the ratio of motor fibers to muscle fibers being called the innervation ratio; (3) area over which the fibers of a SMU are distributed (its territory); and (4) degree to which SMUs are interdigitated within a muscle.

Anatomical and electrophysiological procedures have been used to study the physiology of the SMU. The anatomical approach examines the SMU with microscopic dissection. This procedure is hindered, however, by the complex interdigitation of muscle fibers from several units and by the tedious effort required to dissect out muscle fibers that usually extend the entire length of a muscle.

The electrophysiological approach examines muscle action potentials under various types of nerve fiber stimulation. This procedure has been aided by the Buchthal electrode, which consists of a needle inserted in the cross section of a SMU's muscle territory and contains within it twelve separate electrodes spaced only 1 mm apart, each referenced to the grounded needle. Several characteristics have been inferred by using this electrode arrangement which permits the examination of discharges of individual motor fibers over precise topographical

areas (Buchthal, et al., 1957a, 1957b).

One of the most important findings from these studies is the discovery that SMU waveforms can be characterized by their duration, waveshape, and amplitude--all of which remain constant under most conditions (Kahn, et al., 1971; Basmajian, 1967a; Basmajian & Cross, 1971; Buchthal, 1960; Close, 1964; Petersen & Kugelberg, 1949). The range of values which these parameters may take, however, is heavily influenced by the method of signal detection used (Kahn, et al., 1971).

Voluntary Control of SMU Discharges

Several studies have been influential in developing methods whereby a SMU discharge may be voluntarily controlled. Adrian & Bronk (1928) developed a method by which an audio output of muscle activity could be obtained by amplifying muscle action potentials and using them as an input to an audio amplifier. In a series of studies at Harvard University laboratories (Smith, 1934; Lindsley, 1935; Gilson & Mills, 1940, 1941; Norris & Gasteiger, 1955), several observations of the relationship between SMU discharges and voluntary muscle contractions were made. First, SMU discharges are absent when a muscle is relaxed. Second, the rate of a SMU discharge increases with harder contractions. Moreover, other SMUs are activated (recruited) when muscle contraction is increased further. Two quantitative measures for describing ongoing muscle activity that emerged from these studies were (1) frequency of a SMU discharge and (2) number of SMUs being discharged.

Harrison & Mortensen (1960, 1962) described human Ss who could selectively activate and control specified SMU potentials. These findings and the development of fine-wire bipolar electrodes (Basmajian & Stecko, 1962) have led Basmajian and his colleagues to develop and refine methods for controlling SMU discharges (Basmajian, 1963, 1967a, 1972; Basmajian, Baeza, & Fabrigar, 1965; Simard & Basmajian, 1967).

SMU Methodology Used for Acquiring Voluntary Control

Methods enabling S to acquire control over SMU discharges fall in the general category of biofeedback studies. The standard procedure involves monitoring (recording) some biological event, amplifying that event if necessary, selecting some portion of the signal and presenting it back to S via some sensory channel as externalized feedback. Obtaining this information about on-going biological activity enables S to alter that activity. In the last ten years, a growing number of studies have appeared in the literature indicating that an organism can voluntarily control physiological processes which normally are beyond conscious control. Some of the complex processes cited by Nowlis, Kamiya, Ornstein, & Criswell (1970) that have been controlled are EEG activity, heart rate, EMG, skin temperature, blood pressure, vasodilation, GSR, and blood flow in certain organs.

The training procedure developed by Basmajian for producing voluntary control over the SMU discharge has several stages: (1) fa-

miliarization with feedback for various degrees of muscle contraction; (2) relaxation of muscle to show absence of SMU activity; (3) contraction of muscle at low levels of tension to produce distinct SMU discharges; (4) selection of one SMU discharge (as characterized by its distinct waveform or sound) to control; (5) altering the rate of SMU discharges with changes in muscle contraction; (6) suppression of other SMU discharges by changing degree of contraction or by altering position of limb; (7) activation of the selected SMU upon command; (8) production of different patterns (single discharges, double discharges, etc.); and (9) control over more than one SMU discharge that is recorded by the electrodes.

The literature reports that voluntary control can be demonstrated under the following conditions:

(1) An SMU has been controlled on an on-off basis producing an isolated discharge of the unit (Gilson & Mills, 1940, 1941; Harrison & Mortensen, 1960, 1962; Basmajian, 1963).

(2) Simple patterns of discharge of an SMU have been produced, such as double, triple, and quadruple groupings (Harrison & Mortensen, 1960, 1962; Basmajian, 1963, 1967a; Basmajian, et al., 1965; Simard & Basmajian, 1967; Quigley, 1968; Powers, 1969; Zappala, 1970).

(3) Multiple SMU discharges (3-12) have been individually isolated and brought under pattern control (Harrison & Mortensen, 1960, 1962; Basmajian, 1963, 1967a, 1972; Basmajian, et al., 1965; Simard &

Basmajian, 1967; Wagman, Pierce, & Burger, 1965).

(4) Given a period of practice at isolating individual SMUs during which time S learns to identify individual SMU discharges in the population (3-12) by waveform shape, a specific SMU discharge from the population can be recruited on demand (Basmajian, 1963, 1967a, 1972; Basmajian, et al., 1965; Petajan, 1969; Petajan & Philip, 1969).

(5) With training, some Ss have recalled a selected SMU discharge when they have been deprived of the extrinsic sensory auditory and visual feedback information that was originally used to gain control over the SMU (Harrison & Mortensen, 1962; Basmajian, 1963, 1967a, 1972; Carlsoo & Edfeldt, 1963; Basmajian, et al., 1965; Quigley, 1968).

(6) SMU discharges have been controlled in respect to a time signal. Most of these studies were primarily involved in measurement of RT of SMU discharges (Quigley, 1968; Kimm, 1969; Sutton & Kimm, 1969, 1970; Thysell, 1969).

(7) Two SMU discharges have been individually isolated and then controlled in a time-locking relationship, one to another (Powers, 1969).

(8) Since the earliest studies (Adrian & Bronk, 1929; Smith, 1934), electrical silence was maintained prior to activation of an SMU under control.

Variables Affecting Voluntary Control of SMU Discharges

The search for variables which affect voluntary control may be divided into two categories: (1) S characteristics, and (2) situational

variables. Basmajian (1963) has roughly categorized Ss according to their ability to control SMU discharges as related to the complexity of task performed, the speed with which control is obtained, and the consistency in control over time. Several S characteristics have been studied regarding variables which may facilitate or interfere with control. Apparently age, sex, manual skill, education, intelligence, and personality do not consistently affect SMU performance, although there are exceptions. One study (Zappala, 1970) reported that more males were able to reach a control criterion than females. Untrained females made more errors (35 per cent) than trained females, untrained males, and trained males combined (20 per cent). Basmajian (1965, 1967a, 1972) reported that "nervousness" tended to affect SMU performance although some "nervous" Ss showed good control and some "relaxed" Ss showed poor control. Some decrement in performance, both in the size of the SMU discharge amplitude and the control exhibited over SMUs, was reported by Ss having ischemia (Simard, Basmajian, & Janda, 1968) and by thalidomide children (Simard & Ladd, 1969). Simard (1969) showed that although children could isolate SMU discharges, they had a decreased ability to maintain fine motor control over long periods of time.

The situational factors that may affect SMU performance center primarily around: (1) training procedures used; (2) type of externalized feedback used; (3) electrode configuration used; and (4) muscle site selected.

RT of SMU Discharges

The simple RT task has been utilized as one quantitative measure for assessing SMU control because of procedural simplicity for S and because basic stimulus and response parameters, which are fairly well known on overt responses, provide a frame of reference for comparative studies (Thysell, 1969). Studies investigating RT of SMU firings have had as their goals the (1) investigation of fine control capabilities of SMU discharges (Quigley, 1968; Kimm, 1969; Thysell, 1969); (2) comparison of control parameters and differential effects on SMU discharges within different muscle groups (Quigley, 1968; Kimm, 1969; Sutton & Kimm, 1969); and (3) testing of the effects of alcohol on fine motor performance (Sutton & Kimm, 1970).

Results of these studies follow two primary dimensions: a comparison of SMU RT with GMR RT and the determination of the effects of experimental and procedural variables on SMU RT.

Comparison of SMU RT with GMR RT

All except one SMU study (Thysell, 1969) have shown longer SMU RT than GMR RT latencies. The special control process required for SMU discharge has been suggested as a reason for slower SMU RTs (Sutton & Kimm, 1969). In addition, large variability has been noted: trials occurred in which SMU RT was as slow as 1 sec and as fast as the fastest GMR RT. Requiring Ss to rehearse SMU firings between trials (a method of maintaining control throughout an experimental ses-

sion) lowers measures of RT central tendency and reduces variability (Kimm, 1969; Sutton & Kimm, 1969).

One study (Thysell, 1969) found bimodal SMU RT distributions. When SMU RT and GMR RT distributions were compared, one SMU peak occurred below and the other above the median GMR RT. Adequate controls showed that this result was not due to inadvertant cueing of Ss by relays preceding the visual response signal, leading Thysell to hypothesize two underlying processes for SMU RT. One process which generates SMU RTs slower than GMR RTs was accompanied by some antecedent movement of the little finger, hand, or arm; the second process, which generates SMU RTs faster than GMR RTs, was an "automatic" one in which the SMU discharge somehow "becomes conditioned" to response signal. He is now using delayed auditory feedback and refractory period designs to explore these hypotheses.

Sutton & Kimm (1969, 1970) suggest that the simple RT task which utilizes a SMU discharge is not simple RT because S must select one given SMU from among the population of quiescent SMUs in the muscle. Slower SMU RTs are a result of more complex functioning within the central nervous system as a result of the requirement to discriminate among and suppress these other SMU discharges.

Variables Found to Influence SMU RTs

Alcohol. Sutton & Kimm (1969) found that SMU RT following alcohol consumption shifted median RT latency from 273 msecs to 352

msecs. Although variability of RTs did not change, RT distributions had fewer brief RTs and a larger number of long RTs in all Ss and muscle sites tested. Their conclusions were that SMU RT and EMG RT (time elapsed between response signal and electromyographic recording of a finger movement) measures taken together produce more sensitive measures of alcohol effects than measures obtained from GMRs (key presses) alone.

Modality of Externalized Feedback. Quigley (1968) found that auditory feedback was superior to all forms of visual feedback even when auditory feedback was delayed up to 100 msecs. This is in agreement with S's preference for auditory feedback from all other SMU studies.

Recording Sites Utilized. Sutton & Kimm (1969) studied the differences between biceps brachii and triceps brachii and found that SMU discharges from triceps consistently had shorter RT latencies and less variability than those from biceps. Quigley (1968) reported even briefer RT latencies in abductor pollicis brevis when compared to flexor pollicis brevis. Sutton & Kimm (1969) reported that SMU discharges in abductor pollicis brevis have briefer RTs than SMUs in biceps brachii, triceps brachii, and extensor digitorum communis. Kimm (1969) did not find significantly different results in RT latencies between abductor pollicis brevis and adductor pollicis muscles. Sutton & Kimm (1969) found it difficult to establish a basis for RT differences among muscles although limited

data on innervation ratios of these muscles suggest that shorter RT latencies occur in muscles with higher innervation ratios. Differences in muscle spindle populations within muscles were deemed unlikely because there does not appear to be a high density of muscle spindles in proximal musculature.

Type of SMU Response Required. Instructing S to produce one SMU discharge, two rapid discharges of the same SMU (doublet), or other patterns with the selected SMU resulted in longer RT latencies and variability than either EMG responses or key presses in the same muscle (Quigley, 1968). Mean inter-spike-interval between the two discharges of a doublet, however, was much shorter than activation of the first SMU in the response, indicating that once an SMU has been activated, further activation of that SMU requires less central processing time. Inhibition of a chain of SMU responses is faster than activation of a SMU. Kimm (1969) found median RT latency for stopping repetitive discharges to be 178 msecs as compared to 383 msecs for activation of the same SMU. Kimm asserts that inhibition often occurred as quickly as 75 msecs following stimulus presentation.

Method of RT Analysis. Because he found that multiple responses had shorter median RTs, Quigley (1968) recommended that RTs from correct RT trials (activation of only one selected SMU) be analyzed separately from trials in which more than one unit was fired. Sutton & Kimm (1969) reported that repetitive discharges of the SMU occurred

frequently when S continued to attempt to reduce SMU RT. As did Quigly, they reported shorter median SMU RTs for trials with multiple SMU discharges.

Effects of FP Size on SMU RT

Sutton & Kimm (1969; 1970) did not use a ready signal but varied intertrial intervals from 1 sec to 15 secs. They reported Ss were sometimes unable to produce a SMU discharge after the longer interstimulus intervals. This they attributed to kinesthetic or proprioceptive factors associated with extended periods of quiescence.

Only one study (Thysell, 1970) systematically tested for FP effects on SMU RT. Thysell combined RTs at each of three FP sizes used (500, 1000, and 1500 msecs) in his exploration for contaminating variables that may have produced bimodal RT distributions. However, the resulting RT distributions were all bimodal, leading him to conclude that FP size did not have a significant effect on the distribution.

CHAPTER III

METHODS

Subjects

Two male and four female human subjects (Ss) participated in the RT study. One other S was unable to complete three sessions and was not included in the results. Ss' ages ranged from 20 yrs to 48 yrs with an average age of 29.8 yrs. All Ss had extensive knowledge of SMU performance but differed in the amount of actual training. Most Ss had some prior experience with SMU training using intramuscular electrodes, but only two Ss previously had attempted to isolate SMUs with surface electrodes. Their amount of previous experience ranged from a period of 1 week to 16 yrs. Three Ss had practiced in a RT paradigm with SMU responses, one S using surface electrodes and the other two using intramuscular electrodes.

No S reported an intake of alcohol or medications in the 12-hr period preceding each session. Two Ss reported drinking one or two cups of coffee prior to each session.

Procedure

Each S participated in three sessions lasting from 1 hr and 15 mins to 2 hrs and 45 mins. Each session consisted of two sets of

GMR RT trials and five sets of SMU RT trials. Each set consisted of 30 trials with 10 trials having 2-sec FPs, 10 trials having 5-sec FPs, and 10 trials having 10-sec FPs. FPs were ordered so that each FP size was preceded by the three FP sizes an equal number of times. Orders of FPs were preprogrammed into a PDP-12 computer so that each trial was automatically controlled. Number and length of FPs were not revealed to S.

The purpose of the experiment was explained to S, and a consent form was signed at the beginning of the first session. Personal histories revealing information about age, recent drug intake, and prior SMU experience also were obtained.

Standardized instructions which included procedures on electrode placement, SMU isolation, practice, and RT trials were read to each S. The general procedures of SMU isolation and training set forth by Basmajian and his colleagues (Basmajian, 1963, 1967a, 1972; Basmajian, et al., 1965; Simard & Basmajian, 1967) were used, although individual instructions and training techniques often became necessary during SMU isolation and practice periods.

Physical Setting

S was located in a room adjacent to equipment room and was seated in a padded reclining chair with arm rests. Angle of chair was adjusted for each S so that he was comfortable and experienced no strain in viewing either RT stimuli or the oscilloscope used in providing feed-

back of muscle activity. Light from an adjacent room produced diffuse lighting.

Two stimulus lights used in the RT task were located approximately 5 ft in front of S. The ready signal (a red light) was located to the left of the response signal (a white light). A digital display for RT feedback was directly below both lights. The oscilloscope on which visual feedback appeared was to the right of the display, approximately in the two-o'clock position and about 3 ft from S's eyes. Audio feedback of muscle activity was presented through a loudspeaker located about 2 ft directly behind S. There was no competition between oscilloscope and RT stimuli during the RT tasks since visual feedback was presented only during the isolation and training sessions.

S was always in audio contact with experimenter (E) through a two-way intercom located on S's left side. It was necessary only for S to speak to be monitored by E. E was unable to observe S during the RT trials.

Apparatus in the equipment room was located in a semicircular arrangement. From left to right, apparatus consisted of a teletypewriter, PDP-12 computer, Hewlett-Packard 14-channel FM tape recorder, an 8-channel Grass polygraph, and a rack including a storage oscilloscope and a custom-built amplitude threshold detector. The arrangement allowed one person to supervise the experiment and to monitor any activity that would require manual intervention over the other-

wise automatic operation. E was able to monitor the oscilloscope during both FP and response interval and had sufficient time to view results from the previous trial that appeared on the teletypewriter.

Electrode Preparation

Beckman miniature bipolar surface electrodes were placed over the abductor digiti quinti (AD-V) muscle of the preferred hand using a modification of the "skin-drilling" technique described by Schackel (1959). The outer layer of skin was scrubbed with a gauze containing Offner electrolytic paste to remove the cornified layer of skin. The use of a sterile lancet to prick the skin directly below the center of each electrode was a departure from the Schackel procedure. The 2-mm diameter of each electrode well was filled with Offner electrolytic paste and secured over the skin with adhesive collars. Electrodes were always attached in a plane longitudinal to the length of muscle fibers with a center-to-center distance between electrodes of 1.2 cm. "Skin-drilling" has two distinct advantages over conventional surface electrodes: (1) an improvement of signal quality and (2) guides for electrode placement in the next sessions from two distinct marks left by drilling. Electrode leads taped to back of the hand allowed freedom of hand movement without interfering with electrode placement. A small 1-1/2-in by 3-in silver-plated brass plate was attached to lower arm for optimum grounding. The ground lead was connected to the Grass preamplifier signal ground terminal.

Following electrode placement, S was seated in the testing room. To insure that muscle activity was present on the monitors, electrode placement was checked by having S abduct the small finger in a horizontal place away from the hand. The amount of activity with finger extensions and flexions also was noted. Noise interference was minimized by either adjusting the position of electrode leads or the electrodes themselves.

S relaxed his hand to provide a quiescent baseline and a measure of the amount of system noise present. The Background Threshold Gain on the threshold discriminator was adjusted so that no logic pulses were generated for signals occurring below the quiescent baseline. Logic pulses generated for pulses above the baseline were treated as muscle activity, although not necessarily SMU discharges.

GMR RT

GMR RT sets were given before isolation of SMU responses and after SMU trials. Pilot data dictated that GMR RT sets not be interspersed with SMU RT trials because of difficulty in reisolation of previously trained motor units.

S was given audio and visual feedback of amplified muscle activity via loudspeaker and oscilloscope, respectively. Prior to RT trials, S practiced abducting the small finger to activate the monitored muscle and to become familiar with feedback. Muscle activity from gross movements of the finger appeared as a burst of spikes as in "integrated"

electromyograms. Except in slight movements, distinct SMU discharges could not be identified.

Signals used in the GMR RT task consisted of onset of ready signal and onset of response signal. Ready signal remained on throughout the variable FP, and both ready signal and response signal remained on during the 2-sec test interval. Neither light was on during the 8-sec intertrial period. When the muscle was activated by movement, the first distinct pulse above the quiescent baseline generated a logic pulse that was detected by the PDP-12 computer, which in turn activated a relay to present RT in msecs on the digital counter. Thus, S received immediate knowledge of his RT results.

The following instructions were given for the GMR RT task:

> This is a task to determine how fast you can react to light with a movement of your small finger. The two lights in front of you will be turned on in a specific order. The red light will always come on first and is a signal for you to keep the muscle relaxed, that is, you will not hear any muscle activity in the loudspeaker. Any activity detected when the red light is on alone will be considered an error. At a short period later, the white light will come on. This time between the two signals will not always be the same. The white light is a signal to activate the muscle as quickly as possible by moving your small finger outward (E demonstrates). The time required to make the movement to the light will appear on the digital counter. The time will be in milliseconds so that your reaction time in seconds will be the total score divided by 1000. Your objective is to make the reaction time as small as possible, making sure you do not move before the white light comes on. In addition, failure to respond within two secs after the onset of the white light is considered an error. Are there any questions?

Ten practice trials were given to insure that the instructions were understood and to give S an opportunity to ascertain the amount of move-

ment which would provide optimum RTs.

The following measures were collected for each of 30 trials in a GMR RT set and displayed on the teletypewriter during the intertrial interval: (1) the number of pulses discharged during the FP; (2) the time the first pulse (if any) was discharged during the FP; (3) the number of pulses discharged during the test interval; and (4) the time of the first pulse during the test interval (S's RT).

A correct trial consisted of a FP having no discharges and a test period with at least one detected muscle spike. An "anticipation" error was a trial consisting of one or more muscle spikes during the FP. A "no response" error was a trial in which no muscle spikes were detected in either the FP or test interval.

SMU Isolation

SMU isolation involved the selection of one motor unit from among those monitored by electrodes. All Ss were thoroughly acquainted with Basmajian's method of SMU isolation, both from previous SMU training and from experience as laboratory personnel.

SMU isolation proceeded through several stages designed to shape gross muscle contractions into voluntary discharges of a SMU. The procedure was carried out in the presence of both audio and visual feedback of the amplified muscle activity, which provided S with important information regarding muscle activity. Stages involved in SMU isolation included muscle relaxation, muscle activation and feedback

correlation, SMU selection, and SMU control.

Ideally, during the muscle relaxation stage, S relaxed the small finger, providing a quiescent baseline that appeared as a straight line trace on the oscilloscope and silence from the loudspeaker. When system noise was detectable, the oscilloscope was not a straight line and a "60-Hz buzz" was heard over the loudspeaker. This noise was easily differentiated from muscle activity.

When relaxation was achieved, S was instructed to increase contractions in the AD-V muscle by slowly abducting the small finger. Attention was focused on the increase in muscle activity present in the feedback as a larger abduction was made. S abducted and relaxed the finger several times to become familiar with the level of muscle activity present during different movements. S then concentrated on making finer movements which resulted in distinct SMU discharges rather than the integrated EMG spikes seen in harder contractions.

Once distinct discharges were being produced, S's task was to select one SMU from among those being discharged and to suppress the others. When suppression of other SMUs was achieved, the selected SMU was made to discharge at a constant rate. The oscilloscope showed distinct spikes, having either a monophasic, biphasic, or polyphasic waveform, appearing on the baseline at intervals corresponding to frequency of SMU discharges. Distinct "pops" appeared over the loudspeaker each time the SMU was fired. The basic criterion used in identi-

fication of the discharge as a SMU was the reliability of its waveform in successive firings and the compatibility with SMU parameters given by Basmajian (1967b), Buchthal (1960), Close (1964), and Kahn, et al., (1971).

When S had difficulty suppressing other motor activity other than the selected SMU discharge, one or more of the techniques below were employed: (1) S completely relaxed the muscle and then made maximal contractions and relaxations in an alternating fashion; (2) he tried isolating the SMU with the hand in different positions; or (3) he attempted to isolate a different SMU. As a last resort, electrodes were placed on a different location over the AD-V muscle. The particular method used to suppress other motor activity was an individual procedure.

Following suppression of extraneous SMU discharges, S practiced voluntary control over the selected SMU discharge. Rate of SMU discharges was varied by increasing and decreasing the frequency of firings. S then concentrated on slowing down the rate to a single firing once every 1 or 2 secs. Finally, S started with a relaxed baseline, fired the selected SMU, and returned to the relaxed muscle state.

Several tasks were employed to make the SMU discharge more nearly approximate the response signal required in the RT task. First, S practiced turning the SMU "on" and "off," i.e., starting at a relaxed state, discharging the SMU once, and returning to the relaxed state. If S failed to turn the SMU discharge "off," more than one discharge of

that unit occurred, producing a multiple number of discharges. If other SMU discharges were not suppressed, more than one SMU would be discharged. S practiced throwing the unit singly, first upon his own silent command and then upon a verbal command by E. After 10 trials of having S throw the unit on a verbal command by E, S indicated when he was ready to proceed to the RT practice trials.

The time of the isolation period was recorded along with other special procedures used, such as changing SMUs, hand positions, or electrode positions.

Following the selection of an SMU to be used as a response, controls of the amplitude threshold discriminator were set to provide an output logic pulse on the occurrence of that SMU discharge. Any other SMUs fired above the quiescent baseline but not with the selected SMU's window generated logic pulses on another channel. Therefore, occurrences of SMU firings of both the selected SMU and other SMUs within pick-up range of the electrodes were obtained in order to (1) determine the number of firings during FP and test intervals of the RT task and (2) provide control pulses to activate relays that provide additional feedback to S about his ongoing performance. Amplitude, duration, and waveform characteristics of each selected SMU discharge were recorded along with logic settings for the baseline threshold, upper and lower thresholds for selected SMU discharges, and gain settings on both preamplifier and driver amplifier. A Polaroid snapshot

of the SMU waveform was taken after it was "captured" on a storage oscilloscope.

SMU RT

The format of the five SMU RT sets in each session was the same as that employed for GMRs with the exception of type of response required and additional measures obtained. At the onset of ready signal and during the FP, S was required to maintain muscle silence. At the onset of the response signal, S was required to discharge the selected SMU once, being careful to suppress all other extraneous SMU discharges during the test interval. During the 8-sec intertrial period, S could either practice firing the selected SMU, stretch his hand, or remain relaxed.

The PDP-12 computer counted, stored, and displayed on the teletypewriter (1) the number of times both the selected SMU and other SMUs were discharged in both the FP and test interval; (2) the time elapsed between the onset of the ready signal and the discharge of the selected SMU and/or other SMUs; and (3) the time elapsed between the onset of the response signal and the discharge of the selected SMU (S's RT) and/or other SMUs.

The printout was used for an off-line classification of SMU responses. All trials could be sorted into two main classes: correct and incorrect responses. A correct response was one with no muscle activity detected in FP, the selected SMU fired only once in the 2-sec

test interval, and no other SMU discharges detected during the test interval. All other trials were considered incorrect (or discarded in case of equipment malfunction). Four types of incorrect responses were identified. "Anticipatory" errors (detection of muscle activity in FP) and "no response" errors (failure to detect muscle activity in either FP or test interval) were defined the same as in GMR RT trials. Two additional types of errors were recorded. A "multiple" response was defined as more than one discharge of the selected SMU in the test interval, i.e., S was unable to "turn the unit off" after the first discharge. An "extraneous" trial was one in which one or more SMUs other than the selected SMU was discharged during the test interval.

Apparatus

A functional description of the apparatus used in this study is presented below under six categories: (1) transducing and amplifying equipment, (2) muscle and RT feedback equipment, (3) stimulus equipment, (4) logic and control equipment, (5) monitoring equipment, and (6) storage equipment. A more complete description of individual devices may be found in Appendix B.

Transducing and Amplifying Equipment

The transducing and amplifying apparatus monitored the electrical activity of the muscle and amplified the signal to a level sufficient for (1) providing feedback of that activity to S; (2) detecting the occur-

rence of SMU discharges within the muscle activity; and (3) monitoring and storing the signal.

Muscle and RT Feedback Equipment

Feedback devices provided S with information needed to control the voluntary discharges of SMUs and to determine the speed of muscle response (GMR or SMU) to the response signal used in the RT task.

Signal Lights

The signal lights were two 5-watt Neon bulbs powered by a 5-volt DC dry cell battery and mounted horizontally to each other in a custom-built aluminum frame.

Logic and Control Devices

The logic and control devices served two primary purposes: (1) to detect SMU discharges from ongoing electromyographic signals and to provide digital logic representations of those events, and (2) to synchronize environmental stimuli to S's behavior so as to properly assess RT performance.

Monitoring Devices

The monitoring devices provided E with immediate information about muscle activity and a visual means of correlating muscle activity with stimulus events in the environment.

Storage Devices

The storage devices provided permanent storage of real-time experimental data and descriptions of RT performance and accuracy.

Storage was on three media: paper, magnetic tape, and Polaroid film.

CHAPTER IV

RESULTS

Selection and Analyses of Data

Selection of Data for RT Analysis

Data excluded from RT analyses included (1) trials from the first session, (2) first trial in each set, and (3) trials with incorrect responses. Apparently the first session served as a training procedure for four Ss (S1, S2, S4, and S6) as indicated by their extremely low percentages of correct trials (26.2 per cent) over the first three sets. In addition, there was an unequal number of FP combinations in the first session which biased an analysis of the effects of preceding FP size toward some of the FP combinations. For two Ss (S2 and S3), data from GMRs were unavailable. For these reasons, only data from the last two sessions were included in all analyses.

The first trial from each set was excluded from analyses because there was no preceding trial and because RTs often were longer in relationship to other trials in the set.

Following the recommendation of Quigley (1968), trials were separated into correct and incorrect trials. A gross comparison of RTs of correct trials with RTs of incorrect trials showed that Ss re-

sponded differently over the three sessions with RTs becoming shorter for correct trials and longer for incorrect trials.

Grouping of Trials by FP Combinations for Hypothesis Testing

The statistical treatment of SMU and GMR responses was the same. First, for each S, correct trials from all sets in each of the last two sessions were separated according to nine FP combinations presented (2/2, 5/2, 10/2, 2/5, 5/5, 10/5, 2/10, 5/10, and 10/10). A FP combination designates FP size of a trial and FP size of preceding trial, e.g., the FP combination 5/2 indicates a trial having a 2-sec FP size preceded by a trial with a 5-sec FP size.

Basic Unit of Measurement for RT Speed and Accuracy

For the testing of FP Condition and Session effects of each hypothesis, median RTs for each S in each of the last two sessions were calculated for each FP condition and used as the basic measure of response speed. Median RTs were used instead of mean RTs because of the large number of SMU RTs that were over 1 sec. Percentage of correct responses under each FP condition was used as the basic unit of response accuracy. The number of correct trials per session was converted to percentages because S2 received only four sets of 30 trials in Session Three and because there was a small inequality in number of trials under each condition.

A randomized block factorial ANOVA (RBF-332) (Kirk, 1969, Pp. 237-241) was used to test for differences among FP conditions and

sessions of each dependent variable. Tests for symmetry of variance-covariance matrices (Kirk, 1969, p. 139) and additivity of block and treatment effects (Kirk, 1969, p. 137) were conducted to insure that the assumptions of the model were upheld. In instances where the variance-covariance matrix lacked symmetry, a Geisser-Greenhouse Conservative F test (Kirk, 1969, p. 142) was conducted. Results from these ANOVAs for both GMR and SMU responses are described in the following sections. For each test, a probability less than .05 was selected as the basis for rejection of the null hypothesis.

FP Effects on GMR RTs

Absolute Effect of FP Size (FP), Preceding FP Size (PFP), and Their Interactions (RFP)

Median RTs of each FP combination of the last two sessions for each S are shown in Table 1.

RTs from correct GMR trials (those with no muscle activity in FP) grouped by size of immediate FP are shown in Figure 1. RTs of correct GMR trials grouped by size of preceding trials are shown in Figure 2. RTs from correct GMR trials grouped by relative FP sizes of successive trials are shown in Figure 3.

GMR RT ANOVA is shown in Table 2. Significant differences were found due to size of immediate FP (Treatment A) and to sessions (Treatment C) but not due to size of preceding FP (Treatment B) nor

Table 1. Median GMR RT Latency (in msecs) for Each FP Combination of Last Two Sessions

Subject	Size of Preceding FP					
	Two Seconds		Five Seconds		Ten Seconds	
	Sn 2	Sn 3	Sn 2	Sn 3	Sn 2	Sn 3
	Two-Second Immediate FP					
1	231	208	246	237	234	278
2	348	278	325	340	382	342
3	419	284	307	271	324	338
4	307	286	323	348	317	293
5	388	368	393	328	354	304
6	322	298	327	306	291	297
	Five-Second Immediate FP					
1	212	210	209	224	222	218
2	380	277	298	291	324	313
3	312	262	310	252	265	269
4	258	286	420	276	348	292
5	322	323	318	298	342	289
6	290	301	275	234	239	263
	Ten-Second Immediate FP					
1	241	227	228	205	244	229
2	277	293	293	271	287	320
3	253	300	268	235	280	252
4	295	272	293	298	375	315
5	326	245	283	272	346	242
6	278	270	248	279	346	279

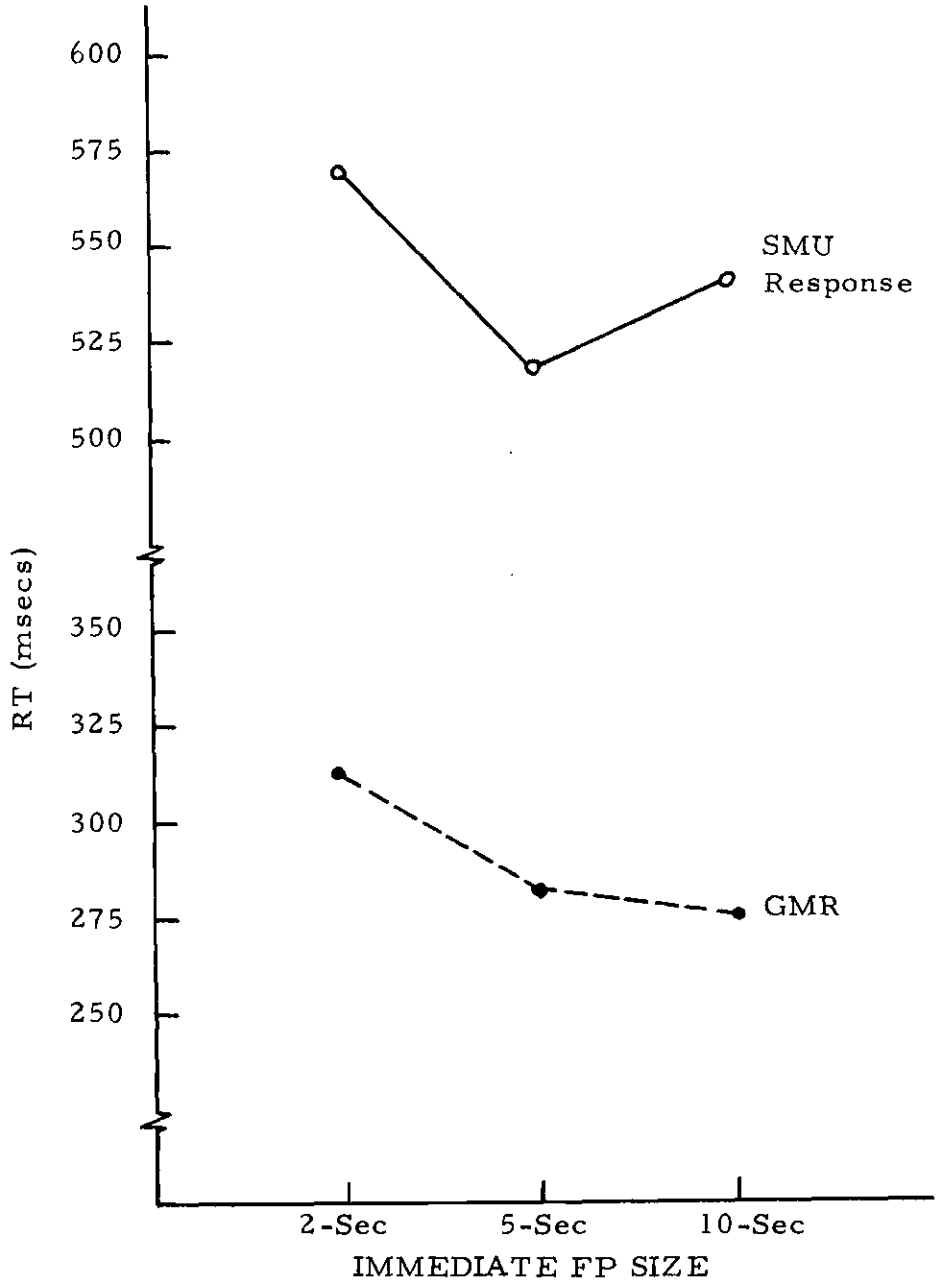

Figure 1. Effects of Immediate FP Size on RT of GMR and SMU Responses

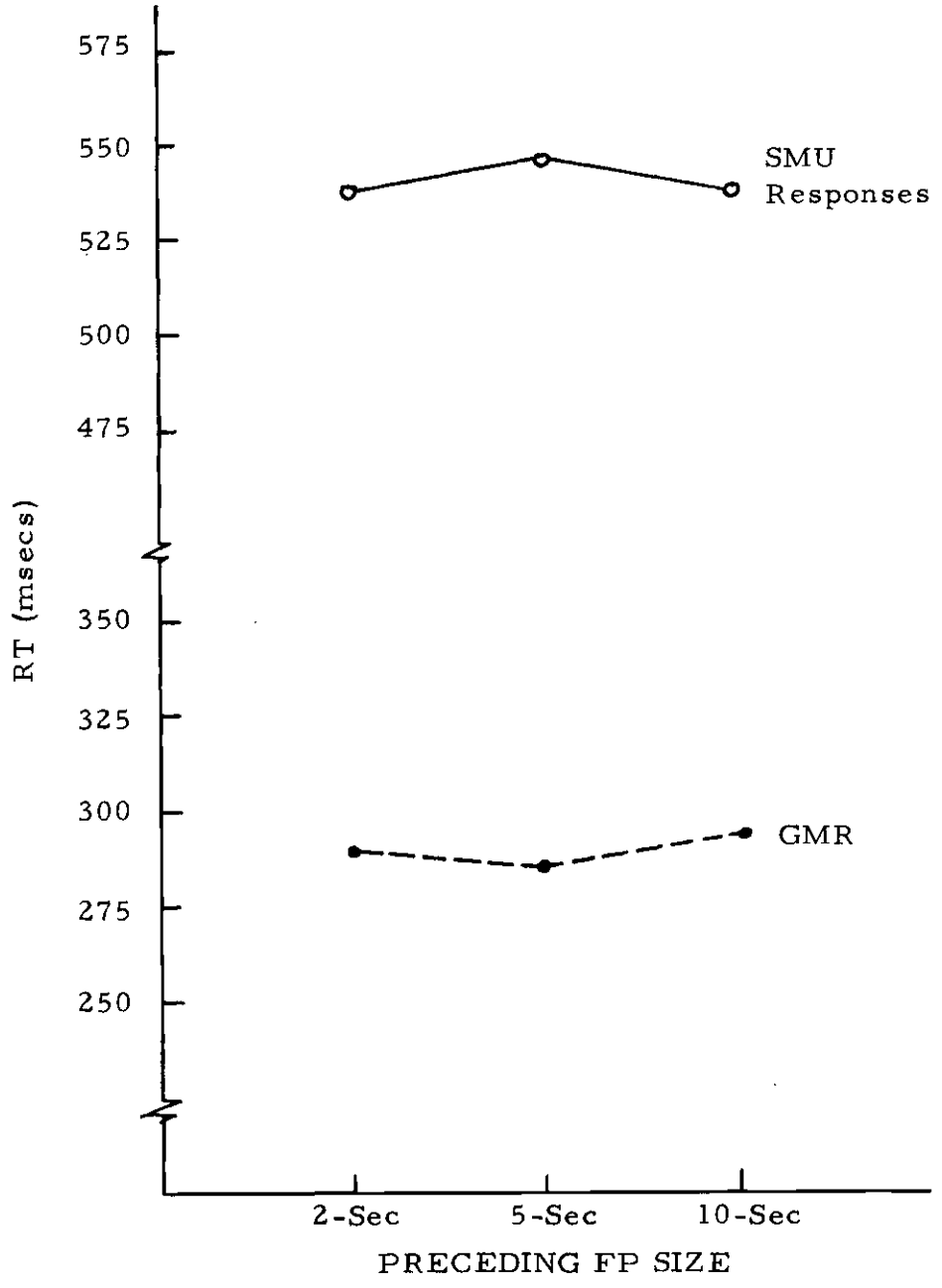

Figure 2. Effects of Preceding FP Size on RT of GMR and SMU Responses

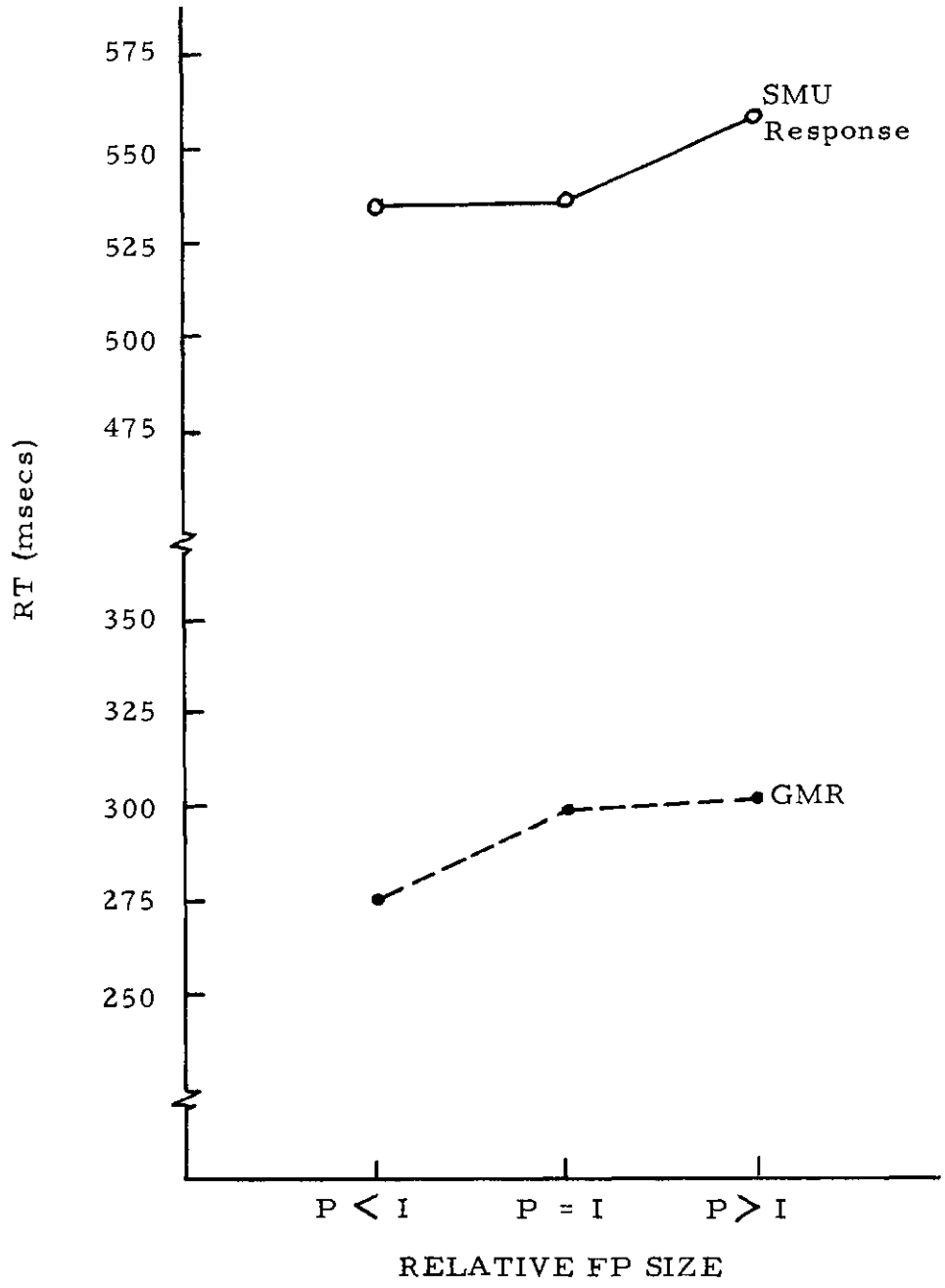

Figure 3. Effects of Relative Size of Preceding FP (P) to Immediate FP (I) on RT of GMR and SMU Responses

Table 2. Analysis of Variance for GMR RT

Source	df	MS	F
Subjects (S)	5	20499.16	12.80*
Treatments	17		
Immediate FP (A)	2	12672.12	9.15*
Preceding FP (B)	2	746.93	0.59
Sessions (C)	1	14630.08	14.28*
A X B	4	935.87	0.46
A X C	2	87.19	0.04
B X C	2	57.33	0.03
A X B X C	4	2194.82	1.37
Residual	85		
A X S	10	1384.58	0.86
B X S	10	1257.72	0.79
C X S	5	1024.39	0.64
A X B X S	20	2021.57	1.26
A X C X S	10	2001.71	1.25
B X C X S	10	1827.09	1.14
A X B X C X S	20	1601.50	
Total	107		

*$p \leq .05$.

their interactions (Treatment AB). No treatment by S interactions were found to be significant.

A test for linearity of trend found the linear component to be significant for immediate FP size ($F = 14.47$, $df = 1, 10$).

FP Effects on SMU RTs

Absolute Effect of FP Size (FP), Preceding FP Size (PFP), and Their Interactions (RFP)

Median RTs of each FP combination of the last two sessions for each S are shown in Table 3.

RTs from correct SMU trials (those with no muscle activity in FP and only the selected SMU fired once during the test period) grouped by size of immediate FP size are shown in Figure 1. RTs of correct SMU trials grouped by FP size of the immediately preceding trial are shown in Figure 2. RTs from correct SMU trials grouped by relative FP sizes of successive trials are shown in Figure 3.

SMU RT ANOVA is shown in Table 4. There were no significant differences due to immediate FP (Treatment A), preceding FP (Treatment B), their interactions (Treatment AB), nor to sessions (Treatment C). Overall Ss by sessions (Treatment CS) interaction was significant.

Tests for linear trend did not show any significant differences.

Table 3. Median SMU RT Latency (in msecs) for Each FP Combination of Last Two Sessions

Subject	Size of Preceding FP					
	Two Seconds		Five Seconds		Ten Seconds	
	Sn 2	Sn 3	Sn 2	Sn 3	Sn 2	Sn 3
	Two-Second Immediate FP					
1	682	578	584	521	723	534
2	640	676	662	630	709	642
3	611	450	571	510	667	476
4	633	600	593	824	775	601
5	499	552	504	441	523	480
6	440	447	394	526	404	393
	Five-Second Immediate FP					
1	744	362	666	491	595	468
2	517	637	558	581	545	705
3	565	412	588	512	822	305
4	571	474	792	497	624	591
5	424	378	510	433	475	390
6	403	418	382	371	498	378
	Ten-Second Immediate FP					
1	626	471	594	472	551	466
2	636	639	471	646	458	634
3	571	369	952	572	494	605
4	867	1002	887	363	644	748
5	410	354	469	411	433	385
6	359	412	445	338	386	359

Table 4. Analysis of Variance for SMU RT

Source	df	MS	F
Subjects (S)	5	17.53	7.67*
Treatments	17		
Immediate FP (A)	2	2.30	1.98
Preceding FP (B)	2	0.09	0.16
Sessions (C)	1	12.09	3.15
A X B	4	0.67	0.69
A X C	2	0.99	2.18
B X C	2	0.19	0.41
A X B X C	4	2.31	1.91
Residual	85		
A X S	10	1.15	0.96
B X S	10	0.54	0.44
C X S	5	3.84	3.17*
A X B X S	20	0.96	0.80
A X C X S	10	0.45	0.37
B X C X S	10	0.46	0.39
A X B X C X S	20	1.21	
Total	107		

*$p \leq .05$.

Rank Analysis of SMU RTs

Because SMU RT distributions of FP conditions showed peaks often occurred in the same order as peaks in GMR RT distributions, and to eliminate some of the effect of larger variances found in SMU RT distributions, Friedman two-way ANOVA by ranks was performed for each FP condition. A probability less than .05 was selected for rejection of the null hypothesis.

For each S, size of immediate FP having the shortest median RT was assigned the rank of one and immediate FP size having the longest median RT was assigned the rank of three. A Chi square of 4.152 ($df = 2$) was not significant. Likewise, size of preceding FP having the shortest median FP was assigned the rank of one and preceding FP size having the longest median RT was assigned the rank of three. A Chi square of 1.15 ($df = 2$) was not significant. These tests support the findings obtained from the RBF ANOVA described above.

Rank Correlation of GMR RTs with SMU RTs

Ranks were assigned to all nine conditions in both GMR and SMU responses with the shortest median RT given a rank of one. Spearman's coefficient of rank correlation $p = 0.56$ was obtained between the two sets of measures. This correlation was not statistically significant ($t = 1.79$, $df = 7$). There were insufficient grounds for saying that FP size affects SMU and GMR RTs in the same manner.

FP Effects on Accuracy of SMU Responses

Over the last two sessions, 62.6 per cent of all SMU trials had correct responses. To determine whether absolute size of FP, absolute size of FP of preceding trials, and relative size of successive FPs affected accuracy of SMU responding, a randomized block factorial ANOVA was used. Percentage of correct trials of each S in each session was used as the basic unit of measure.

Percentages of correct SMU trials for each FP condition appear in Table 5 and Figures 4, 5, and 6. Results of the ANOVA are shown in Table 6. Significant differences were shown for immediate FP (Treatment A), but not for preceding FP (Treatment B) nor their interaction (Treatment AB). Within Ss preceding FP by Ss (Treatment BS) and sessions by Ss (Treatment CS), interactions were significant as were Ss overall (Treatment C).

A test for linear trend for immediate FP condition was significant (F = 14.438, df = 1, 10). Tests for linear trend did not show significant results in either preceding FP (PFP) nor their interaction (RFP).

Accuracy of GMR Responses

In the last two sessions, over 90 per cent of all GMR trials were correct responses. Because of this high percentage of correct responses, the effects of different FP conditions on accuracy were not tested with the randomized block factorial ANOVA as was done with SMU responses.

Table 5. Percentage of Correct SMU Trials for Each FP Combination of Last Two Sessions

Subject	Size of Preceding FP					
	Two Seconds		Five Seconds		Ten Seconds	
	Sn 2	Sn 3	Sn 2	Sn 3	Sn 2	Sn 3
	Two-Second Immediate FP					
1	93	93	61	83	60	53
2	75	87	61	61	50	80
3	67	60	71	77	80	63
4	73	40	59	40	40	73
5	67	93	44	100	60	87
6	67	62	67	69	60	71
	Five-Second Immediate FP					
1	75	56	80	53	72	78
2	83	62	50	40	80	40
3	69	87	87	53	78	89
4	62	56	60	40	67	28
5	37	69	47	93	44	79
6	56	67	60	59	50	59
	Ten-Second Immediate FP					
1	71	47	75	81	73	53
2	50	59	61	69	77	53
3	65	69	12	73	50	85
4	53	47	50	25	50	60
5	41	76	50	75	33	87
6	53	63	37	61	33	76

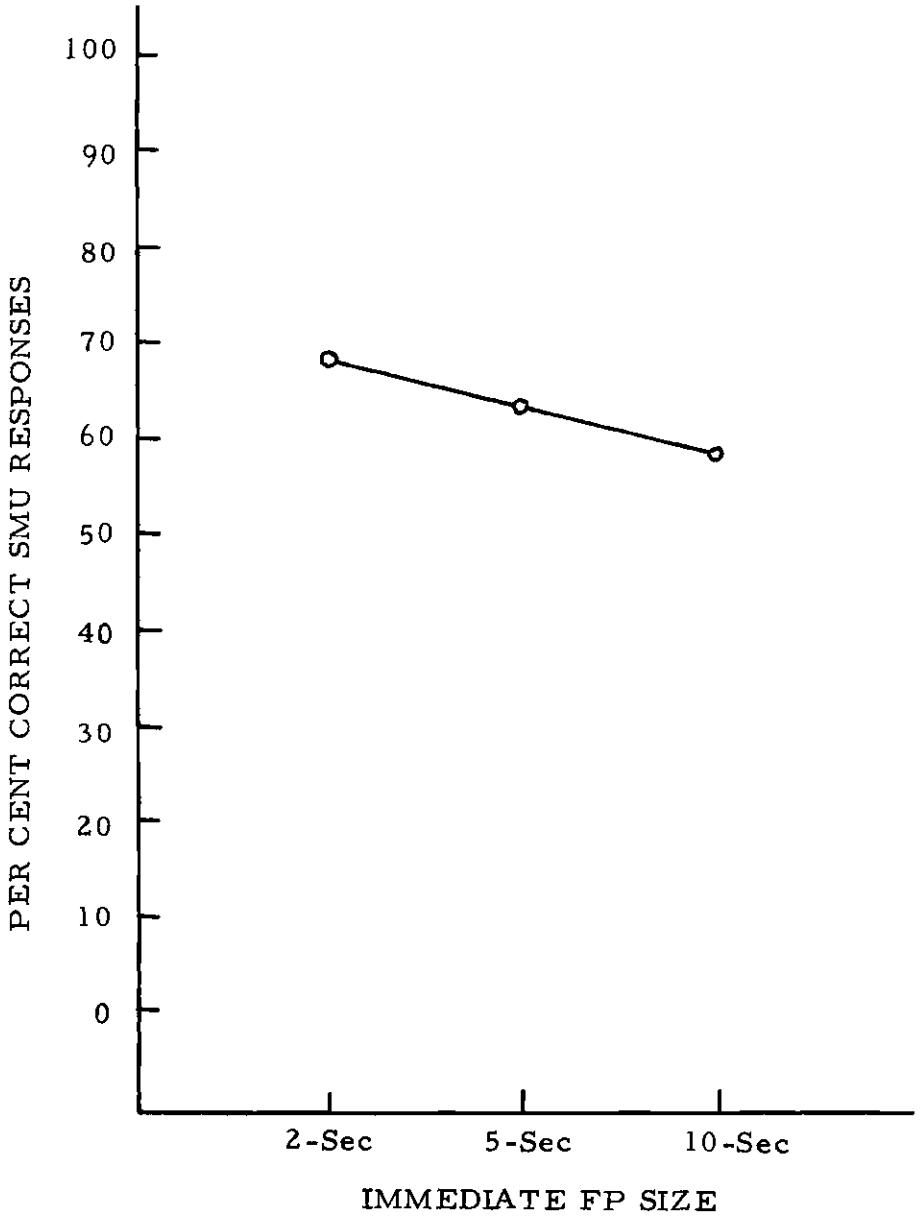

Figure 4. Effects of Immediate FP Size on Accuracy of SMU Responses

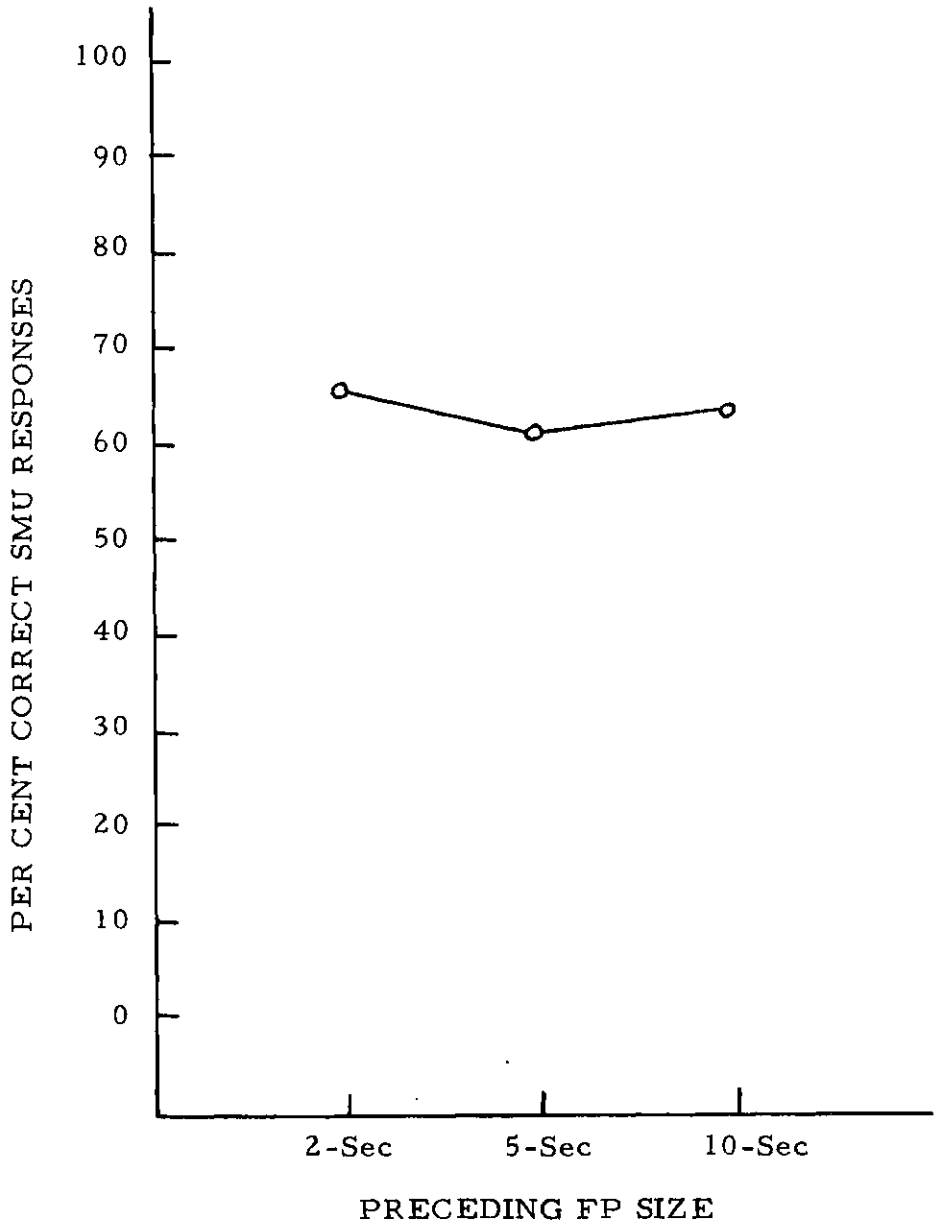

Figure 5. Effects of Preceding FP Size on Accuracy of SMU Responses

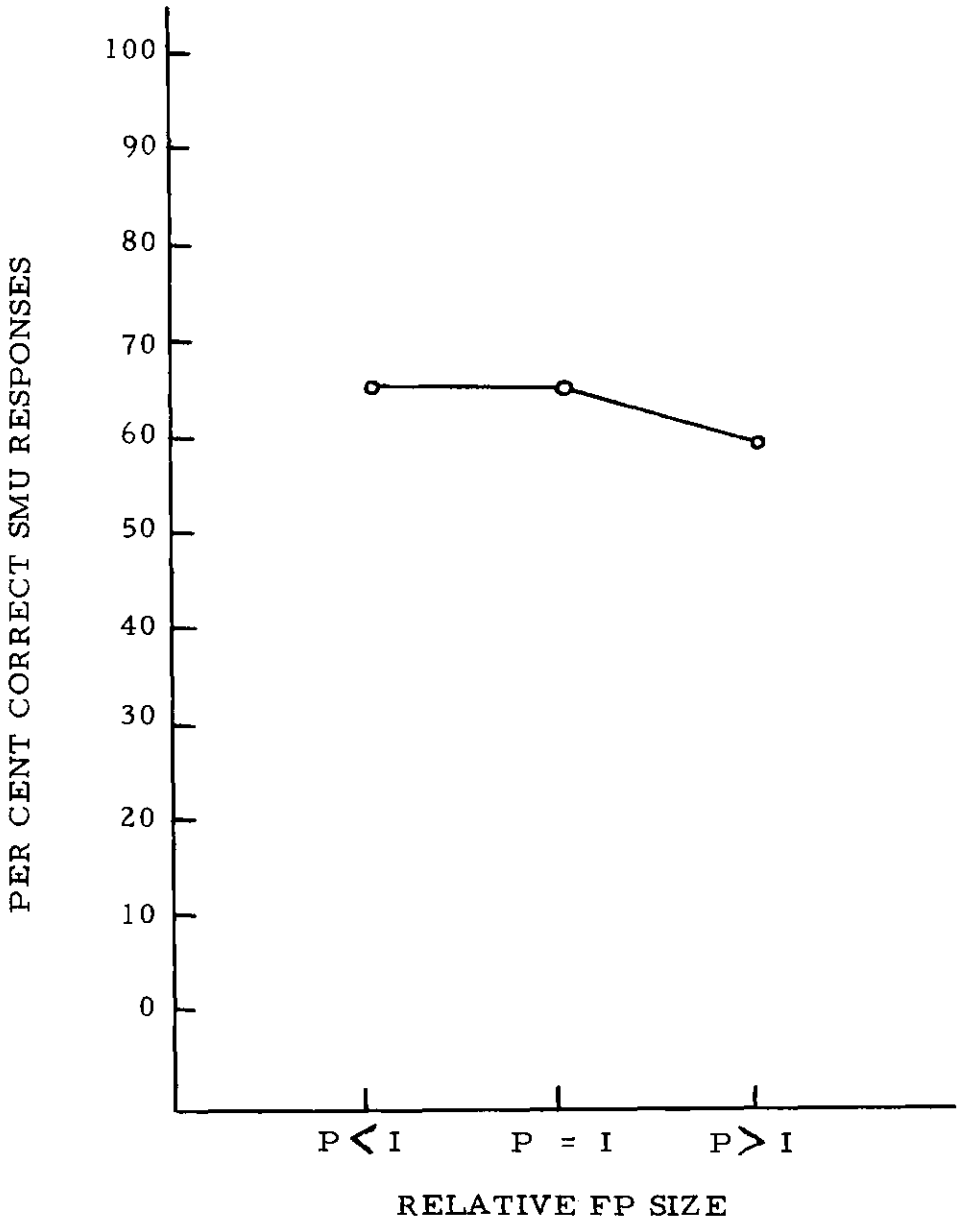

Figure 6. Effects of Relative Size of Preceding FP (P) to Immediate FP (I) on Accuracy of SMU Responses

Table 6. Analysis of Variance for SMU Accuracy

Source	df	MS	F
Subjects (S)	5	849.49	3.79*
Treatments	17		
Immediate FP (A)	2	851.03	7.41*
Preceding FP (B)	2	193.70	1.74
Sessions (C)	1	867.00	0.60
A X B	4	97.81	0.56
A X C	2	547.86	2.35
B X C	2	101.86	1.21
A X B X C	4	137.06	0.61
Residual	85		
A X S	10	114.78	0.51
B X S	10	111.28	0.49
C X S	5	1442.96	6.43*
A X B X S	20	173.89	0.78
A X C X S	10	232.75	1.04
B X C X S	10	84.17	0.37
A X B X C X S	20	224.32	
Total	107		

*$p \leq .05$.

CHAPTER V

DISCUSSION

RTs of GMR Responses

Initial Observations

The present study, using an abduction of the small finger of preferred hand as a response, found a longer median RT to a visual stimulus (c. 300 msecs) than Woodworth & Schlosberg (1954, p. 16) reported as typical for practiced adult subjects (c. 180 msecs). The present finding is also inconsistent with that of Sutton & Kimm (1970), who reported that EMG recordings of gross muscle movements are equivalent to measures of RT latencies and distributions of RTs of gross key presses. Listed below are several conditions found by other investigators to lengthen RT. In that these conditions were present in the procedure of this experiment, they may in part account for longer median RTs.

(1) Sets of RT trials with varying FPs (a heterogeneous set) produce longer RT latencies than RT trials with FPs all of the same size (Botwinick & Brinley, 1962; Karlin, 1959; Klemmer, 1957).

(2) Heterogeneous sets of RT trials with a large range of FP sizes produce longer RT latencies than heterogeneous sets with a short

range of FP sizes (Drazin, 1961; Klemmer, 1956; Naatanen, 1970). The range of FPs in this study was from 2 to 10 secs. A smaller range, e.g., 2 to 4 secs or 8 to 10 secs, would have produced shorter RT latencies.

(3) Ss were required to maintain a relaxed muscle at the site of recording during the FP of each trial. Normally when key presses are used as responses, silence of EMG activity is not required during FPs. Studies by Davis (1970), Freeman (1938), Freeman & Kendall (1940), Katzell (1948), Kennedy & Travis (1947a, 1947b), and Travis & Kennedy (1947) have shown electromyographic tension present that builds up from onset of ready signal to onset of response signal both at proximal site of response and in distal musculature. Speed of response was directly related to amount of tension present in FP. Requiring S to inhibit this tension at the primary recording site might have resulted in increased RTs because initiation of response was delayed until after response signal was presented.

(4) Responses involving abduction produce longer RTs than flexions.

(5) Reaction to onset of a stimulus has on occasion produced longer RT latencies than reaction to offset of a stimulus (Teichner, 1954).

(6) Trials at beginning and end of a session often contain "warm-up" and "fatigue" effects which increase RT latencies (Woodrow, 1914;

Karlin, 1959). GMR trials were used in the first and last set of each session so that intervening sets would be successive sets of SMU responses, in order to minimize the chance of losing control over the selected SMU discharge used as a response.

Although these conditions may have resulted in increased overall RT latencies, the effects should have been constant for both types of responses, GMRs and SMU discharges. There seems to be a reliable trait of reaction time present in different degrees in different individuals (Baxter, 1942). Whether differential FP effects of the nature described in the literature occurred for both GMR and SMU responses presents a more important question.

FP Effects on GMR Responses

The primary hypotheses tested regarding FP effects on RT latencies were: (1) RT is inversely proportional to immediate FP size; (2) RT is not affected by absolute value of preceding FP size; and (3) RT is inversely proportional to interaction between preceding FP and immediate FP size. The first two hypotheses were confirmed by the results of the GMR RT ANOVA and provided a positive indication that the present procedure could be used to assess the effects of FPs on SMU RT latencies. It also produced a baseline of performance from which SMU RT performance could be compared.

Failure to replicate previous findings regarding the interaction between preceding FP and immediate FP size (Klemmer, 1956; Karlin,

1959; Zahn, et al., 1963) is evidenced by the high variability between Ss and their inconsistencies from Session Two to Session Three. Although four Ss (S1, S2, S3, and S4) showed RT patterns in Session Three consistent to literature findings, i.e., longest RTs occur when a long FP size precedes a short FP size, this pattern was seen only for S2 and S5 in Session Two. Another possible reason for failing to replicate Hypothesis Three was that the number of EMG trials for each FP combination was too small to obtain a representative measure of central tendency for RT latency.

RTs of SMU Discharges

Initial Observations

In determining the effects of FP size on RT speed and accuracy when SMU discharges were used as a response, several observations can be reported. First, it was possible to record electromyographic activity using surface electrodes. The recordings, after amplification, had characteristics of SMU discharges recorded with surface electrodes (Kahn, et al., 1971) and by other types of electrodes (Basmajian, 1967; Buchthal, 1960; Close, 1964). Successive recordings of selected SMU discharges were reliable as measured by overlapping triggered recordings on a storage oscilloscope, by photographic records of oscilloscope recordings, and by polygraph records.

Second, Ss were able to isolate one SMU discharge from among

discharges recorded by surface electrodes. A quiet baseline was first obtainable by requiring a relaxed muscle. Unit isolation was obtainable by methods described by Basmajian and his colleagues (Basmajian, 1963, 1967a, 1972; Basmajian, et al., 1965; Simard & Basmajian, 1967). The time required for Ss to obtain voluntary control over a selected SMU was highly variable. Some Ss were able to isolate and control a SMU discharge within seconds after receiving augmented feedback; others required up to an hour. Changes in limb position, selection of a different SMU to control, and changes in electrode placement were sometimes necessary for S to produce a usable response.

Third, Ss were able to produce a correct response to response signal under test conditions on over 60 per cent of all trials in the last two sesssions. This was as high as 90 per cent for some Ss over an entire session. Improvements were made in accuracy following the first session, but performance in the third session did not always exceed that in the second.

Finally, automatic electronic detection of SMU discharges from an electromyographic recording was possible and digital outputs were obtainable to represent the SMU discharge selected for control and for other SMU discharges that were treated as errors. These digital outputs were usable for computer inputs in detection of SMU occurrence, recording RT latencies, determining accuracy of a trial, and triggering RT latency feedback on a digital counter to S after each trial. Changes

in skin conductance which resulted in slight shifts in recorded waveform amplitudes could be compensated for by on-line adjustments of the threshold detector during the experiment.

These initial observations gave confidence that the response to be analyzed in the RT experiment was being produced, recorded, and detected for adequate assessment of FP effects on RT.

Median SMU RTs

Median SMU RTs in the present study were about 500 msec whereas median RTs in previous SMU studies ranged from 200-350 msec (Kimm, 1969; Quigley, 1968; Sutton & Kimm, 1969, 1970; Thysell, 1969). Several possible variables may have accounted for this large difference in median RTs.

(1) The present study utilized surface electrodes while each of the previous studies utilized intramuscular electrodes.

(2) Previous experience by Ss with intramuscular electrodes produced negative transfer when surface electrodes were used. This is supported by the fewer number of long RTs from the two Ss who had not previously used intramuscular electrodes (S5 and S6).

(3) Although the attempt was made to make the basic training procedures in the present study the same as those utilized in previous SMU RT studies, there is always the possibility of differences in individual instruction.

FP Effects on SMU Responses

Results showed immediate FP size, preceding FP size, and relative size of two successive FPs not to affect speed or accuracy of SMU discharges. Several results suggest that other conditions present may have masked FP effects. First, median RTs for SMU responses were large, suggesting that Ss did not have good control of the response. Second, range and variability of RTs in SMU discharges were large, indicating that voluntary discharge of SMUs was a relatively complex response under these test conditions. Third, Ss were without muscle feedback during the FP of each trial, resulting in a significantly larger number of errors on trials having immediate FPs of 10 secs and possibly increasing RTs on those trials. This is consistent with earlier findings (Harrison & Mortensen, 1962; Basmajian, 1972) which reported that although Ss can recall a selected SMU discharge when deprived of extrinsic sensory feedback information, performance is poorer and dependent on length of time in which feedback has been removed.

Comparison of FP Effects on RTs in SMU and GMR Responses

ANOVAs showed immediate FP size to have significant effects on GMR RTs but not to have significant effects on RTs of SMU discharges. Results from the Friedman two-way ANOVA by ranks and Spearman coefficient of rank correlation between GMR and SMU RTs insured that it

was not the absolute size of the median RTs which masked this lack of significance. Examination of individual performance showed the effects of immediate FP size on GMR RTs was consistent from Session Two to Session Three in all but S4. Furthermore, the 2-sec FP condition produced the longest RTs in all Ss on both sessions except S4 in Session Two. This was not true for the SMU responses. A FP length was not likely to have the same effect on different Ss nor the same effect in the second session as in the third session for a given S.

The results of the present study did not support the initial prediction that FP effects would be in the same direction when RTs of SMU discharges were used as a response as when GMR RTs were used. However, this is not to imply that the present study showed SMUs and GMRs to obey different principles, as the present study failed to reject the null hypotheses. The most parsimonious conclusion is that until further research shows RTs of voluntary discharged SMUs and GMRs (such as those controlling finger movements) have similar properties, we cannot legitimately apply conclusions based on RT research to SMU discharges monitored by surface electrodes.

APPENDIX A

INSTRUCTIONS

APPENDIX A

INSTRUCTIONS

Session One

This is a study to determine the effects of FP size on SMU RT to a visual stimulus. The general procedure is as follows: (1) surface electrodes will be attached to the abductor digiti V muscle of the preferred hand; (2) one motor unit will be isolated from among those being recorded and you may practice with that unit until you feel you have it under voluntary control; (3) a short number of RT trials will be given to familiarize you with the procedure and to obtain a baseline of RT performance.

This is a description of a single RT trial. A red light will go on to indicate that the trial is beginning. During the period when only the red light is on, you should maintain a quiet baseline of muscle activity. Any motor unit activity detected will be considered an error. A white light will go on at various times after the red light. The white light is a signal for you to discharge the selected SMU as quickly as possible, without activating any surrounding units. The same unit should be fired on each trial and not switched during a given set of trials. Discharging the unit correctly will stop the digital counter and your reaction time

will appear. If the unit is not fired, the counter will not stop counting until it reaches 2 seconds. After you have discharged the unit correctly, wait until both the red and white lights go out before firing any other units. When both lights are out, you may practice firing the selected SMU or move your hand to a more comfortable position. There will be approximately 8 seconds between trials.

The following types of responses will be considered as errors for a given trial: (1) firing the unit selected for control more than once during the response period when the white light is on; (2) firing any other units while the white light is on; (3) failing to fire the selected SMU during the 2-second response period; and (4) firing any unit during the FP when only the red light is on.

After each set of trials is completed, a short rest period will be given. You may practice discharging the unit, sit silently, or walk about. An intercom is provided so that you may communicate with the experimenter. All you need to do is to talk into the receiver.

Remember that the length of FP is varied from trial to trial. You will be unable to anticipate the onset of the response signal. Are there any questions?

Sessions Two and Three

The procedure in this session will be the same used in the last session. Let me review that procedure for you. First, electrodes will

be placed over the same muscle site. You will begin with a set of GMR RTs, followed by five sets of SMU RTs, and concluded with a set of GMR RTs.

During the set of GMR RTs, you will discharge a burst of muscle activity when the white light comes on. This activity should occur as fast as possible without regard about which motor units are being discharged. Remember to keep a quiet baseline when only the red light is on.

After the GMR trials, you will isolate one SMU from among those being recorded. Practice with this unit until you feel it is under control.

Use the same RT procedure during each of the SMU RT trials. Remain quiet when the red light is on, and discharge the selected SMU when the white light comes on. If the SMU was correctly discharged, RT will be displayed on the counter. You may practice control over the unit between trials. Remember to discharge only the selected SMU during the response period and to suppress other SMU activity surrounding this unit. Are there any questions?

APPENDIX B

APPARATUS

APPENDIX B

APPARATUS

This appendix is designed to give a more complete description of individual devices used in this study. They are presented under six functional categories.

Transducing and Amplifying Equipment

The transducing and amplifying apparatus monitored the electrical activity of the muscle and amplified the signal to a level sufficient for (1) providing feedback of that activity to S; (2) detecting the occurrence of SMU discharges within the muscle activity; and (3) monitoring and storing the signal.

Beckman Surface Electrodes

Two Beckman miniature skin electrodes, Model Number 650437, were used for bipolar recording of muscle activity. Each electrode consisted of a silver-coated chloride pellet and specially shielded high impedance leads that terminated with a male connector compatible with the Grass Selector Panel.

Grass Selector Panel

The Grass Selector Panel, Model 6E5825B, contained input jacks that routed the signal through shielded cables to the Grass Wide Band

AC Pre-amplifier in the adjacent equipment room. Input Jacks P3 and P4 were used for muscle activity and Jack A1 was used to ground a silver-coated brass plate serving as a ground electrode.

Grass Wide Band AC Pre-amplifier and Integrator

The pre-amplifier presented a high input impedance to the differential input. Its settings were fixed for a low frequency cutoff of 3 Hz. The amplified signal was internally routed to the DC Driver Amplifier.

Grass DC Driver Amplifier

The DC Driver Amplifier, Model 7DAC, was used to further amplify the signal and the high frequency cutoff of 3K Hz was used. Control dials allowed E to select signal polarity, control DC baseline shift, and set the proper amount of amplification. A 60-Hz filter was utilized to reduce the noise and improve signal-to-signal noise ratio.

Muscle and RT Feedback Equipment

Feedback devices provided S with information needed to control the voluntary discharges of SMUs and to determine the speed of muscle response (GMR or SMU) to the response signal used in the RT task.

Grass Audio Monitor

The Grass Audio Monitor, Model AM4A, provided feedback of the amplified muscle activity in the audible range. Control dials included a noise suppressor at 60 Hz and an output level potentiometer for controlling gain.

Tektronix Oscilloscope

A Tektronix 545B Oscilloscope with 1A1 Dual Trace plug-in units was used to provide visual feedback of the amplified muscle activity to S. Sweep speed was set at 10 msecs; amplitude scale was set so that the selected SMU covered 3 to 5 cm; and intensity was set to a level desired by S for easy detection of SMU discharges.

Hewlett-Packard Frequency Counter

A H-P Frequency Counter contained a digital display providing immediate visual feedback of the response RT in msecs. The counter was operated in the Time Interval A-B Mode. Input A, generated by the PDP-12 computer when the response signal occurred, started the counter running at a 1-msec rate. A second relay closure, generated when the PDP-12 detected the correct response, stopped the count.

Monitoring Devices

Monitoring devices provided E with immediate information about muscle activity and a visual means of correlating muscle activity with stimulus events in the environment.

Grass Polygraph Strip Chart Recorder

The Grass Polygraph, Model 7, provided an ink-written record of eight channels plus a timing marker every second. Monitored records included amplified muscle activity, logic output for the selected SMU discharge and other SMU discharges, and binary levels for relays

marking the onset of FP and response intervals. Since the inkwriter does not duplicate muscle activity accurately because of slow pen inertia (Basmajian, 1963), the polygraph record was used primarily as back-up and for permanent storage to provide easily read information regarding the synchrony of muscle responses and logic output.

Tektronix Storage Oscilloscope

The Tektronix Storage Oscilloscope, Type RM564, had a dual trace with 3B3 Time Base plug-in modules. It was used by E as the primary monitoring device for observing muscle activity and setting controls of the logic devices. Sweep speed was set to 10 msecs, and amplitude scale was set so that the selected SMU discharge was 3 to 5 cm high.

PDP-12 Teletypewriter

The PDP-12 Teletypewriter, Type ASR-33, consisted of an input keyboard, output printer, tape reader, and tape punch. As a monitoring device, the teletypewriter printed out results of each RT trial during the 8-sec intertrial interval, thus allowing E to obtain immediate feedback of RT latencies and accuracy. The ASR-33 was connected internally to the I/O bus of the PDP-12 computer.

Logic and Control Devices

The logic and control devices served: (1) to detect SMU discharges from on-going electromyographic signals and to provide digital

logic representations of those events, and (2) to synchronize environmental stimuli to S's behavior so as to properly assess RT performance.

Amplitude Threshold Detector

The amplitude threshold detector was a custom-built device for detecting spiked events (e.g., SMU discharges) from an analog signal (e.g., electromyogram) and for providing digital output pulses on either of two channels depending on amplitude of events detected. Adjustment of the Background Threshold Gain, Lower Amplitude Threshold Gain, and Higher Amplitude Threshold Gain provided: (1) no digital output for signal noise, (2) digital outputs on one channel for the selected SMU discharge, and (3) digital outputs on the other channel for other SMU discharges.

PDP-12 Computer

The Digital Equipment Company PDP-12 Computer was a small (4096 words of memory) on-line computer used to control environmental devices as well as to provide detection, computation, monitoring, and storage functions. PDP-12 controls were through its programmable peripherals: ASR-33 teletypewriter, AD12 analog input channels, DR12 relays, DW12 real-time clock, and TD12 LINCtape.

Each set of RT trials was under complete software control which had provisions for (1) initiating each set via teletypewriter keyboard input; (2) turning ready and response lights on via relays and real-time clock; (3) detecting, counting, and classifying digital inputs represent-

ing selected SMU and extraneous SMU discharges via AD converter; (4) calculating RT in msecs via real-time clock; (5) displaying RT to S on digital counter via relays; (6) printing trial-by-trial results to E on teletypewriter printer; and (7) storing results on LINCtape for further off-line analyses.

Signal Lights

The signal lights were two 5-watt Neon bulbs powered by a 5-volt DC dry cell battery and mounted horizontally to each other in a custom-built aluminum frame. A red plastic cap was used over the ready signal while the response light was covered with a white translucent cap.

Storage Devices

The storage devices provided permanent storage of real-time experimental data and descriptions of RT performance and accuracy. Storage was on three media: paper, magnetic tape, and Polaroid film.

Grass Polygraph Strip Chart Recorder

A description of the Strip Chart Recorder and signal recorded and stored is found under Monitoring Devices.

Hewlett-Packard FM Magnetic Tape Recorder

A Hewlett-Packard FM Magnetic Tape Recorder, Model 3955A, was a 14-channel recorder containing 14 Model 3535A FM record amplifiers and 14 Model 3538A FM reproduce amplifiers. Recordings were made of the same signals recorded on the Strip Chart Recorder.

PDP-12 Teletypewriter

A description of the PDP-12 teletypewriter and its data printout is found under Monitoring Devices.

PDP-12 LINCtape

Following each set of RT trials, the teletypewriter printout was stored permanently on LINCtape in digital form. Each set was stored under a unique file name to allow for retrieval and off-line analysis of RTs.

Tektronix Oscilloscope Camera

A Tektronix oscilloscope camera, mounted over the face of the Tektronix Model RM564 storage oscilloscope, provided permanent analog waveform storage of selected SMU discharges.

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