ON-LINE PROGRAMMING IN SIMPLE MOVEMENT SEQUENCES: AN APPLICATION OF THE PROBE REACTION TIME PARADIGM

by

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ABSTRACT

The main goal of this experiment was to detect on-line programming as it occurred during the execution of forearm extension movements by including a probe reaction time paradigm within an extension-flexion movement task. The experiment included a primary and a secondary task condition and subjects performed these tasks in both single and dual-task situations. For the primary task in the single task condition, subjects performed forearm extension (E), and two types of extension-flexion movements for which the time between successive extension and flexion movements was varied (i.e., this time period was 50-100 msec (EFS) or 250-300 msec (EFL)). For the secondary task in the single task condition, subjects wore headphones through which an auditory stimulus (i.e., probe) was delivered at seven positions, either before or after the primary task stimulus. The onset of this probe was determined by either an absolute time interval, or by on-line analysis of EMG and acceleration profile data. Subjects closed their jaw as quickly as possible following the probe. In the dual task condition, the forearm movement and the jaw clench response were performed simultaneously.

The reaction times were comparable for E, EFS and EFL movements in the dual task condition, suggesting that subjects programmed the flexion movement during the execution of the extension movement. By combining probe reaction time measures with those from the initial latency period, a more accurate description could be given of where in time these on-line control processes took place. Specifically, the probe reaction times were lengthened when the probe occurred at the end of the extension movement for EFL movements. It appeared that subjects delayed the execution of the jaw clench response until the programming of the flexion movement had been completed and hence the jaw clench and flexion response were initiated concurrently at this probe position (evidenced by EMG activity of the Masseter and Biceps

muscles). Subjects appeared to use this same strategy for probes occurring during the pause time for EFL movements and at the point at which peak velocity was obtained for EFS movements.

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INTRODUCTION

A commonly observed phenomenon in the production of movement sequences is that the time required to initiate a movement sequence (i.e., reaction time) increases with the number of response elements in the movement sequence. This phenomenon has been referred to as the response complexity effect (e.g., Christina, 1992). Henry and Rogers (1960) were among the first to show this relationship between reaction time and response complexity. Specifically, they demonstrated that a simple key lift response was initiated more quickly than a response composed of a key lift and additional movements to specified targets. More recently, this effect has been investigated using a variety of tasks, including typing (Sternberg, Monsell, Knoll, & Wright, 1978; Sternberg, Knoll, & Turock, 1990), pronouncing word sequences (Eriksen, Pollack, & Montague, 1970; Klapp, 1971; Sternberg, Knoll, Monsell, & Wright, 1988; Sternberg et al., 1990), writing words of different lengths (Hulstijn & Van Galen, 1983; Thomassen & Van Galen, 1992; Van Galen, 1991), making sequential hand postures (Harrington & Haaland, 1987) and executing sequences of gross arm movements (Fischman & Lim, 1991; Norrie, 1967; Ulrich, Giray, & Schäffer, 1990).

In general terms, models that account for the response complexity effect assume that the following processes take place prior to movement initiation. First, an abstract representation of the movement sequence (i.e., motor program) is retrieved from long-term memory and, is then temporarily stored as subprograms in a short term motor buffer. Second, before execution of each individual movement in the sequence, the corresponding subprogram is retrieved from the buffer, unpacked into its constituents and initiated. The model proposed by Klapp (1976, 1977) attributes the response complexity effect to the difference in time needed to read the motor program from long-term memory into a short-term motor program buffer. Alternatively,

Rosenbaum and associates (Rosenbaum & Saltzman, 1984; Rosenbaum, Hindorff, & Munro, 1987) believe the response complexity effect is due to the time required to edit the program while it is in the buffer. Sternberg and colleagues (Sternberg et al., 1978) offer yet another explanation for this effect by attributing the increase in reaction time to the time needed to search the buffer for the subprogram that controls the first part of the movement response. Presumably, the search time increases with the number of subprograms in the buffer. Because these models assume that movement sequences are programmed prior to their initiation (from here on termed pre-programming), they predict a direct relationship between the number of response elements in a movement sequence (i.e., the number of subprograms of the motor program) and reaction time.

Recently, several studies have indicated that there are some conditions in which increases in response complexity do not lead to increases in reaction time. Specifically, researchers have shown that reaction time increased linearly in relation to the number of response elements when movements were completed as fast as possible, but either failed to do so, or did so non linearly when performed at a less than maximal speed (Canic, 1988; Garcia-Colera & Semjen, 1987, 1988; Van Donkelaar & Franks, 1991a, b). Rosenbaum, Hindorff and Munro (1986) have explained these findings by suggesting that in some instances, subjects do not program the entire movement sequence prior to its execution; rather, some aspect of this process carries on into the period of movement execution (from here on termed on-line programming).

Recently, Ketelaars, Franks and Nagelkerke (1993, see Appendix C) designed an experiment to isolate the conditions under which subjects programmed sequences of forearm movements on-line and those in which subjects were forced to preprogram. The movement sequences that were used in this experiment were forearm extension movements and two types of

extension-flexion movements for which the time between successive extension and flexion movements was manipulated [i.e., subjects were instructed to make either a short pause (approximately 50-100 msec), or a long pause (approximately 200 msec)]. The results showed that when the time between successive extension and flexion movements was between 200 and 300 msec, the reaction time did not increase above that of the simple extension movement; When this time was between 50 and 100 msec, the reaction time increased significantly above that of an extension movement. On the basis of these findings, Ketelaars et al. (1993) suggested that subjects were forced to program both the extension and flexion movement prior to movement initiation when the time between these movements was 50-100 msec; When this time exceeded 200 msec, subjects were able to program part of the flexion movement (or the entire flexion movement) after the initiation of the extension movement. Even though these findings suggested that sequences of forearm movements can be programmed on-line when subjects are allowed to pause for a certain amount of time between successive movements, it is not clear at which point(s) during the movement sequence this programming activity takes place. For example, does on-line programming occur at certain positions during the execution of the extension movement, or during the time period between the extension and flexion movement ? In order to gain an understanding of the processes involved in on-line programming it is important to find evidence of it within the movement sequence itself.

Over the past few years, researchers have used several experimental manipulations to identify on-line programming as it occurs within a movement sequence. In a number of studies in which subjects were required to type a series of keystrokes, Ostry (1980, 1983) found that subjects tended to lengthen the inter-response intervals (IRI's, i.e., the time from the beginning of one movement element to the next) in the middle of the sequence. Ostry

hypothesized that this mid-sequence slowing was used by subjects to program the terminal elements in the typing sequence on-line. Studies by Povel and Collard (1982) and Rosenbaum, Kenny and Derr (1983) have also shown that by analyzing variations within IRI's, evidence can be provided that on-line programming takes place as the movement is executed.

Van Donkelaar and Franks (1991a, b) found evidence of on-line programming in a study in which movement speed was manipulated (i.e., movements were either made as fast as possible, or at a slower, more controlled rate). More specifically, they measured the acceleration profiles (i.e., the number of zero-line crossings of the acceleration profile and significant deviations within the acceleration profile) and electromyographical (EMG) profiles (i.e., the relative duration of EMG activity and the specific pattern of EMG activity) from horizontal repetitive arm extension-flexion movements in addition to the reaction time required to initiate such movements. Each of the dependent variables showed that on-line programming had occurred in the slow movement condition. These dependent variables also allowed for the quantification of on-line programming. Specifically, analysis of the relative temporal locations and frequency of the deviations within the acceleration profiles showed that the deviations occurred at specific (and reproducible) points during the slower movements.

Several researchers have used a probe reaction time paradigm to detect on-line programming (e.g., Glencross, 1980; Franks, Wilberg, & Fishburne, 1985; Fleury, Bard, Audiffren, Teasdale, & Blouin, 1994). In probe reaction time studies, subjects are required to perform two tasks simultaneously - a primary task and a secondary task. The point in time at which the secondary task occurs is manipulated in a systematic manner. The general assumption that underlies probe reaction time studies is that individuals possess a fixed total capacity for information processing (also referred to as *attention*; see

McLeod, 1977). As a primary task demands more of this limited capacity, less is available for a concurrent secondary task and the latter deteriorates. Thus, primary task workload is inversely reflected in secondary task performance. It is suggested that if the primary task is entirely preprogrammed, the secondary task reaction times should remain invariant throughout the movement. However, if the movement is programmed on-line, the secondary task reaction times should increase during the parts of the movement at which such processing occurs. Through the use of the probe reaction time manipulation, Glencross (1980) showed evidence of on-line programming during the execution of sequences of forearm movements that varied in complexity. Similar evidence of on-line programming was also found but in a serial pattern learning study by Franks, Wilberg and Fishburne (1985).

From the preceding discussion it appears that both the type of movement sequence used and the speed at which movement sequences are executed are determining factors in the choice of the experimental paradigm used to detect on-line programming. The probe reaction time paradigm is the most desirable experimental paradigm for identifying the temporal location of on-line programming activity during a forearm extension-flexion movement. By including a probe reaction time manipulation within the existing extension-flexion movement task, the present experiment will attempt to detect on-line programming as it occurs within a movement sequence. It is expected that, by looking at changes within the reaction times to the secondary task, inferences can be made regarding the amount of processing that occurs at various times during the extension-flexion movement task.

McLeod (1980) questioned the use of the probe reaction time as an inferential tool. He demonstrated that several confounds within the probe reaction time methodology could make subsequent interpretations difficult. The most obvious was the interference caused by using the same response

modality (e.g., motor, vocal, auditory; also referred to as *structural interference*) for both the primary and secondary task. When McLeod changed the secondary task from a manual to a vocal one, he found a different pattern of secondary task reaction time results. From this he concluded that movements do not have an absolute attentional demand which can be measured by any sort of secondary task. This does not mean that the probe reaction time paradigm is intrinsically incapable of producing information about the primary task. However, it does imply that conclusions about the processing demand of the primary task can only be drawn if it has been demonstrated that a certain phase of the primary task always produces the same pattern of interference irrespective of the secondary task used. Because the main interest of the present study is in the differential processing demands of forearm extension and extension-flexion movements, rather than in absolute attentional demands, McLeod's (1980) criticism does not apply.

In order to keep structural interference to a minimum in the present experiment, a visual stimulus and a forearm movement response were selected for the primary task while an auditory stimulus evoking a jaw clench response was used for the secondary task. The primary task consisted of a forearm extension movement and two types of extension-flexion movements for which the time between successive extension and flexion movements was varied (50 - 100 msec and 250 - 300 msec). It was expected that both the extension and extension-flexion movement with a short time (50-100 msec) at the reversal would be preprogrammed, while the extension-flexion movements with a long time (250-300 msec) at the reversal would be programmed on-line. The secondary task stimulus was designed to occur at various times throughout the planning and production of the primary task. Specifically, the time of onset of the secondary task stimulus was: (a) 150 msec before the onset of the stimulus used to initiate the primary task; (b) 100 msec after the onset of the

stimulus used to initiate the primary task (i.e., during the premotor reaction time period); (c) 30 msec after the onset of EMG activity of the Triceps muscle (prime mover; i.e., during the motor reaction time period); (d) at the point at which peak acceleration and (e) peak velocity were obtained for the extension phase of the movement; (f) at the end of the extension movement; and (g) 50 msec after the end of the extension movement.

The first secondary task stimulus position was selected because of the controversy that exists as to whether movement sequences are programmed prior to or after the imperative stimulus in a simple reaction time paradigm. Klapp (1977, 1980, 1981) has argued that subjects can program movement sequences prior to the imperative stimulus when they know the required movement sequences in advance. However, Canic and Franks (1989) have shown that movements cannot be entirely preprogrammed before the onset of the imperative stimulus. Rather, some time must be spent after the imperative stimulus programming the movement sequence prior to its execution. It was expected that the probe reaction times would be elevated when the secondary task stimulus occurs 150 msec prior to the onset of the primary task stimulus if subjects do indeed program some aspects of the movement sequences prior to this imperative stimulus. If, on the other hand, subjects start the programming of the movement sequence upon presentation of the imperative stimulus, then the secondary task reaction times would not be elevated at this stimulus position.

The second and third secondary task stimulus positions were chosen to address the concerns raised as to the independence of programming functions during the premotor and motor portions of the reaction time. The premotor reaction time is defined as the time from the imperative stimulus to the beginning of EMG activity. It is thought to represent the time needed to centrally organize, translate and channel the appropriate commands to the

musculature responsible for initiating the desired response. On the other hand, the motor reaction time is defined as the time from the beginning of EMG activity to the start of external limb movement. This reflects the duration of non programming events [e.g., electromechanical delay and development of sufficient torque to initiate movement (Anson, 1982)]. It has been argued that, since motor reaction time does not reflect delays associated with central planning, it is important to separate this time out of the reaction time period (Anson, 1989; Christina & Rose, 1985). This more sensitive process allows for better discrimination between the latencies associated with muscular activity and actual limb displacement, thus, leading to a more detailed interpretation of any differences in programming time (Anson, 1982, 1989; Christina & Rose, 1985; Sidaway, 1988). However, Van Donkelaar and Franks (1991a) have argued that if it is assumed that movements can be programmed at any time before or during the execution of a movement sequence, then it appears plausible that this programming can also occur during the motor reaction time period. Similarly, if it is assumed that entire movement sequences are programmed prior to their initiation, then it seems faulty to assume that as soon as the muscles become active, this programming can no longer occur. The present experiment should shed some light on this issue. It was expected that if movement programming takes place exclusively during the premotor reaction time period, the secondary task reaction times would be more elevated when the secondary task stimulus occurs during this time period than when the secondary task stimulus occurs during the motor reaction time period. If, on the other hand, some movement programming does indeed take place during the motor reaction time period, then the secondary task reaction times would also be elevated when a secondary task stimulus occurs during this time period.

The remaining four secondary task stimulus positions were selected because the main focus of the present experiment was to detect on-line programming as it occurred during the execution of a forearm extension movement. Two secondary task stimuli occurred at the point at which peak acceleration and peak velocity were obtained. The remaining two stimuli occurred at the end of the extension movement and during the time between successive extension and flexion movements (i.e., 50 msec after the end of the extension movement). The stimulus positions were determined through on-line analysis of the acceleration profile data. It was expected that the secondary task reaction times would be elevated during parts of the movement at which on-line programming occurs.

METHOD

Subjects

Twelve right-handed male and female university students served as subjects in the present study. All were naive as to the hypotheses under investigation and none had previous experience with the tasks or procedures used. Subjects were paid $ 4 per hour, up to a maximum of $ 16. The experiment was carried out according to the ethical guidelines laid down by the University of British Columbia behavioural sciences screening committee for research and other studies involving human subjects.

Task and Apparatus

This experiment included a primary and a secondary task condition. In the primary task condition, subjects were required to make forearm extension and extension-flexion movements in the horizontal plane, through a range of 45 degrees (from 67.5 degrees to 112.5 degrees - where 180 degrees was defined as full extension). The right forearm was positioned on a manipulandum which consisted of a padded horizontal lever attached to a bearing-mounted vertical shaft, such that the elbow was coaxial with the axis of rotation. The right hand was supinated to grasp a vertical handle at the end of the lever and the position of the handle was adjusted to accommodate for varying forearm lengths. Subjects were secured in their seat with a shoulder harness in order to keep the contribution from the shoulder muscles constant within each movement condition and their arm was secured to the manipulandum with Velcro straps. In addition, the height at which the subjects were seated was adjusted so that the shoulder angle remained constant in the frontal plane across all subjects.

Subjects viewed an oscilloscope screen that was positioned directly in front of them at a distance of 50 cm. On this screen, two "target boxes"

(consisting of four cursors spaced 1 centimeter apart) and a response cursor were displayed. These target boxes were 10 cm apart at the horizontal center line of the oscilloscope screen: 5 cm to the right and left of the center.

An optical encoder (Dynapar E20-2500-130), attached to the shaft of the manipulandum and custom made computer interface card allowed for high speed sampling of the angular position of the manipulandum (the sampling rate was 1000 Hz).

Angular acceleration data were obtained through the use of a Kistler accelerometer (type 8638B50, ± 50 G), positioned at the end of the manipulandum, 42 cm from the center of rotation. Its signal, which was measured in volts, was filtered with an active lowpass filter (Krone-Hite, # 3750) set at 50 Hz and then sampled.

Electrical activity from the medial head of the right Biceps muscle and the lateral head of the right Triceps muscle was monitored using Ag/AgCl surface electrodes (8 mm diameter). The electrical signal from the two sets of surface electrodes was amplified by a multichannel electromyographic (EMG) system (model 544, Therapeutics Unlimited Inc.) and raw amplified EMG signals (maximum ±10 V) were sampled at a frequency of 1000 Hz and stored for subsequent analysis.

Subjects wore headphones through which a secondary task stimulus (a tone with a frequency of 3000 Hz and a duration of 50 ms) was delivered at 7 temporal positions, either before or after the onset of the visual stimulus that was used to initiate the primary task. The onset of the secondary task signal was determined by either an absolute time interval (i.e., 150 msec prior to, or 100 msec after the onset of the primary task stimulus), or by on-line analysis of EMG and acceleration profile data. Subjects were required to close their jaw as quickly as possible following the onset of the secondary task stimulus. In order to evenly spread bite pressure and lessen the potential of tooth impact,

subjects were required to wear a senior sports mouth guard (Rucanor). Electrical activity from the right Masseter muscle was monitored using the same Ag/AgCl surface electrodes as detailed above and the sample frequency, again, was 1000 Hz.

All data were collected and saved on an MS-DOS 386-33MHz personal computer for later analysis. This computer was programmed (Borland Turbo Pascal 6.0) to control the entire experiment.

Independent Variables

Two independent variables were manipulated in the present experiment. The first was complexity of movement response. All subjects completed extension (E) movements and two groupings of extension-flexion (EF) movements. For one group of extension-flexion movements the pause time at reversal was between 50 and 100 msec (i.e., extension-flexion short pause (EFS)). For the second group this time was between 250 and 300 msec (i.e., extension-flexion long pause (EFL)). The pause time was calculated from the angular acceleration profiles and was defined as the time interval between the second zero line crossing of the acceleration profile (at the end of extension) and third zero line crossing (at the beginning of flexion).

The second independent variable that was manipulated was the secondary task stimulus position. The respective positions were: (a) 150 msec before the onset of the visual stimulus used to initiate the primary task (- 150), (b) 100 msec after the onset of the visual stimulus used to initiate the primary task (i.e., during the premotor reaction time (+100)), (c) 30 msec after the onset of EMG activity of the Triceps muscle (i.e., during the motor reaction time (EMG + 30)), (d) when the slope of the acceleration profile was zero (i.e., at peak acceleration (PA)), (e) when the acceleration profile crossed the zero line for the first time (i.e., at peak velocity (PV)), (f) when the acceleration profile crossed

the zero line for the second time (i.e., at the end of extension (END)) and (g) 50 msec after the acceleration profile crossed the zero line for the second time (i.e., 50 msec after the end of extension (END + 50)).

Experimental Procedure and Design

The experiment consisted of two testing sessions, lasting approximately two hours each. During these two sessions, subjects performed the primary and secondary tasks in both single task and dual task situations. At the beginning of the first session, the experiment and task were described to the subjects and informed consent was obtained.

At the beginning of each session, the EMG electrodes were attached to the skin, following standard EMG procedures (Basmajian, 1974; O'Connell & Gardner, 1963). First, the electrode placement area was shaved to remove hair from the electrode site; second, the site was rubbed with an abrasive pad to remove the dead surface layer of skin; and third, the site was cleaned with a solution of 91% isopropyl alcohol. Electrode gel was rubbed into the skin at each electrode site to diminish skin impedances. Each pair of electrodes was filled with electrode gel (Parker Laboratories, Inc., Signa Creme) and affixed to the surface of the skin by double sided adhesive tapes (Converters, Inc., # AET-250). The electrodes were aligned longitudinal to the direction of the muscle fibers and the wires were taped to the skin to prevent movement artifacts. A ground electrode was attached to the left wrist.

During the first session, the order of events was fixed. Trials for the primary task in the single task condition occurred prior to those of the secondary task in the single task condition, because several mean scores obtained during the primary task in the single task condition served as an input to the secondary task in the single task condition. Dual task trials occurred last.

For the primary task in the single task condition, subjects performed one block of seven trials for each of the three primary task movement conditions (E, EFS, EFL). The order of presentation of each movement condition was counterbalanced across subjects to control for any order effects. Each subject was randomly assigned to a predetermined order of movement conditions. In order to discourage subjects from anticipating the onset of the imperative stimulus and responding prematurely, 10 % of trials were catch trials.

The procedure for each trial was as follows. At the start of a trial, the target boxes and response cursor were visible on the oscilloscope screen. Subjects positioned the manipulandum such that the response cursor was centered inside the left target box (designated as -22.5 degrees) and then reported "ready", indicating to the experimenter that the trial sequence should begin. Two seconds after the subjects had reported "ready", the target boxes were removed from the oscilloscope screen for 250 msec. The target boxes then reappeared, signaling the start of the trial (i.e., warning signal). After a variable foreperiod (1500 - 2500 ms), the two target boxes and response cursor were removed from the oscilloscope screen. This served as the imperative stimulus. In the extension movement condition, subjects were then required to move the response cursor to the right target (designated as +22.5 degrees). This movement was therefore an extension of 45 degrees. In the extension-flexion movement conditions, subjects were required to perform an extension movement to the right target, pause for a specified time period and then perform a flexion movement back to the start position. The secondary task stimulus was also presented at various times throughout the movement when subjects performed the primary task in the single task condition, but the subjects were instructed not to react to this stimulus. Once the subjects had completed the required movement(s), the target boxes and response cursor reappeared on the oscilloscope screen for 500 ms, marking the end of the trial.

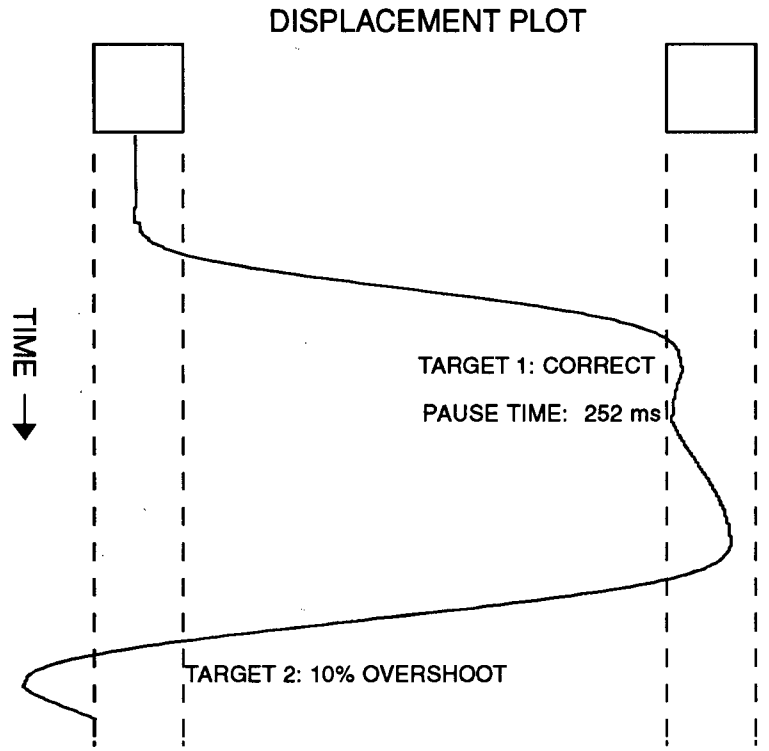
Immediately following each trial the kinematics of the subject's response and the stimulus were displayed on a colour graphics video monitor (Zenith "Flat Screen" ZCM1490) which was positioned directly underneath the oscilloscope. The first display consisted of the subject's displacement during the trial. Two sets of vertical lines on each side of the monitor screen represented the two target boxes and the subject's displacement data were displayed with the X axis representing displacement and Y axis representing time. The second display consisted of the subject's acceleration profile, reaction time and first movement target error (signed constant error in degrees). An example of this type of feedback is given in Figure 1.

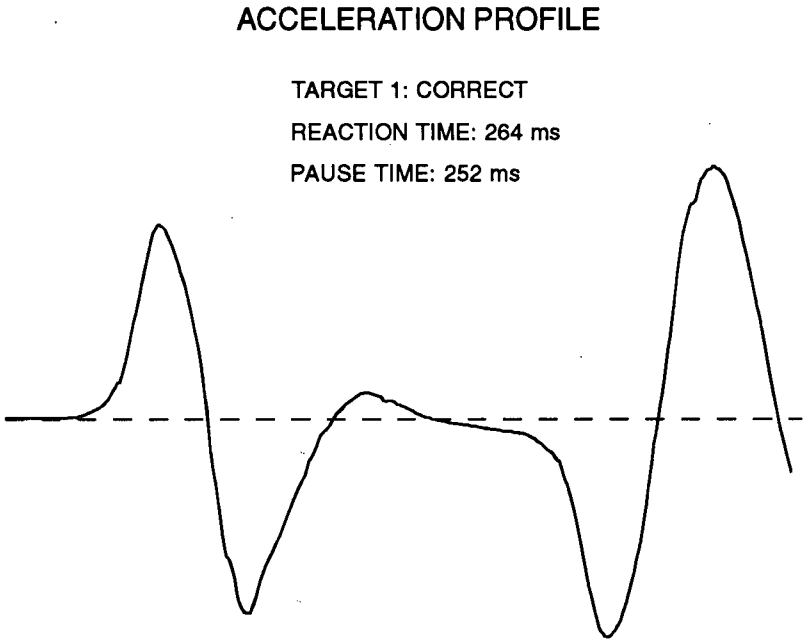
The subject's attention was directed to the first feedback display for accuracy and then the acceleration profile display for trial acceptability as per the required movements and reaction time. The subject was then told that any trials with an error score greater than ± 1.125 degrees, or a reaction time less than 100 msec (indicating anticipation) or greater than 500 msec (indicating a lack of attention) were discarded from further analysis. Additional trials were administered until the subject had performed seven acceptable trials for each movement condition. In Table 30 (See Appendix B) an overview is given of the total number of trials that were rejected for the primary task in the single task condition.

During a catch trial, the variable foreperiod was extended and the target boxes were not removed from the oscilloscope screen. After five seconds the experimenter reported the catch trial to the subjects and recorded any movement as error.

The secondary task in the single task condition consisted of a total of 21 trials, three trials for each of seven probe positions, in addition to 10 % catch trials. Probe position 1 was 150 msec before the onset of the visual stimulus used to initiate the primary task; probe position 2 was 100 msec after this

Figure 1: Example of feedback displays





stimulus. Mean scores for motor reaction time, peak acceleration, peak velocity and first target endpoint for the extension movement condition obtained during the primary task in the single task condition were calculated and these values were used to determine the remaining five probe positions. Subjects did not perform arm movements in the secondary task in the single task condition.

The procedure for each trial in the secondary task in the single task condition was identical to that described for trials in the primary task in the single task condition. Thus, two seconds after the subjects had prepared themselves to respond, the target boxes were removed from the oscilloscope screen for 250 msec. After this time delay, the target boxes reappeared, signaling the start of the trial. Then, after a variable foreperiod, the two target boxes and response cursor were removed from the oscilloscope screen. On 90 % of the trials the imperative stimulus for the secondary task was presented. The order in which the probe positions occurred was determined randomly. Subjects did not receive any feedback on their reaction time to the secondary task stimulus. In Table 31 (See Appendix B) an overview is given of the total number of trials that were rejected for the secondary task in the single task condition.

During a catch trial, the target boxes were removed from the oscilloscope screen, but the stimulus for the secondary task did not occur. After five seconds the experimenter reported the catch trial to the subjects and recorded an error if subjects activated their Masseter muscle (as evident from EMG recordings).

Dual task trials followed procedures outlined earlier. Each subject was randomly assigned to a predetermined order of the 3 movement conditions with 21 trials per condition (3 trials at each of the 7 probe positions). The order of each movement condition was counterbalanced across subjects. In addition,

the order of the secondary task probe positions within a condition was randomized. Subjects were instructed to make the movement response as fast and accurately as possible; they were also advised to respond to the secondary task stimulus as fast as possible, **but to consider the primary movement task a priority**. The feedback that was given to the subjects in the dual task condition was the same as that reported for the primary task in the single task condition. No feedback was given on the reaction time to the secondary task stimulus. In Table 32 (See Appendix B) an overview is given of the total number of trials that were rejected in the dual task condition. It is evident that a large number of trials were rejected in this task condition.

Two types of catch trials (i.e., 'no movement' and 'no tone') were included in the dual task condition. Catch trials were used for two reasons. First, they were included to discourage the subjects from anticipating the onset of the imperative stimulus for either the primary or the secondary task and responding prematurely; and second, based upon a recommendation by Herman and Kantowitz (1970), they were implemented to serve as controls in addition to the controls obtained for the primary and secondary task in the single task condition. The procedure for a catch trial was identical to that described for regular single and dual task trials and both occurred on 10 % of the trials. Subjects were not able to differentiate between regular trials and catch trials.

During a 'no movement' catch trial, only the secondary task stimulus was presented. Subjects were expected to react to the onset of this stimulus by tightening their jaw and to withhold the arm movement response. Due to an error in the computer program that was written to control the experiment, the secondary task stimulus occurred 1500 to 2500 milliseconds after the onset of the warning signal (i.e., at the same relative point in time as the onset of the primary task stimulus in a real trial) and not at one of the seven probe

positions. The experimenter reported the catch trial to the subjects and recorded an error if the subjects moved their arm (as evidenced by displacement). It should be noted here that a 'no movement' catch trial had the same characteristics as a regular trial in which a secondary task stimulus occurred 150 msec prior to the onset of the primary task stimulus. For analysis purposes the performance on 'no movement' catch trials was thus compared to the performance on trials in which a tone occurred at the first probe position (i.e., - 150 msec) for regular single and dual task trials.

During a 'no tone' catch trial, the target boxes were removed from the oscilloscope screen (stimulus for the arm movement) but there was no stimulus (tone) for the secondary task. In this situation, subjects were thus expected to make the arm movement response, but not tighten their jaw. Again, the experimenter reported the catch trial to the subjects and recorded any error (evidenced by EMG activity of the Masseter muscle). To the subjects a 'no tone' catch trial had the same characteristics as a real trial on which the secondary task stimulus could potentially occur after the primary task response had been initiated. The performance on 'no tone' catch trials was therefore compared to the performance on regular trials in which the probe occurred at positions 4 through 7 (i.e., during the movement execution phase). The overall error rate on catch trials was maintained at 9.1 %.

During the second session, subjects performed the same number and type of trials. The order in which the three main conditions (i.e., the primary task in the single task condition, the secondary task in the single task condition and the dual task condition) occurred was counterbalanced. Each subject was randomly assigned to a predetermined order of the experimental main conditions. On both days subjects were allowed several practice trials prior to each block of trials. Day 1 was treated as practice; the data were not analyzed.

EMG Analysis

Among the many methods used in the current motor control research literature for defining the onset and offset times of EMG activity, visual inspection of the raw, or the raw rectified EMG is by far the most widely used (e.g., Anson, 1982, 1989; Carlton, Robertson, Carlton, & Newell, 1985; Christina & Rose, 1985; Fischman, 1984). A second method is to design computer programs that determine the onset time of muscle activation by calculating when the level of activity has reached a value determined by either the product of baseline activity and a constant, e.g., ± 25 micro volts (Sidaway, 1988), or by a certain percentage of the peak amplitude of activity observed for a particular experimental condition, e.g., 10 % of the peak amplitude of the subject's averaged rectified EMG profile (Schmidt, Sherwood, & Walter, 1988).

Recently, Ketelaars, Franks, Sanderson and Nagelkerke (1993) compared the various methods for defining the onset and offset times of EMG activity. It was concluded that when computer algorithms were used, the calculated onset times were overestimated and the offset times underestimated compared to the results of visually inspecting the raw and rectified EMG signal. The method of visual inspection of the raw and rectified EMG, however, did not provide reliable inter- and intra observer results. In order to improve the method of visual inspection, the following procedure was used. The raw EMG signals were first full-wave rectified and then low pass filtered using a fourth-order zero-phase-shift Butterworth filter with a cut-off frequency set at 30 Hz. Following this procedure, the experimenter was presented with a raw, rectified EMG signal (inverted) and a raw, rectified and filtered EMG signal on the computer screen. The experimenter placed a cursor at the first indication of heightened EMG activity above the baseline for each raw, rectified and filtered EMG signal and compared the placement of the cursor to the raw, rectified profile. This method provided reliable inter- and intra observer results (The

inter observer reliability coefficient was 0.87; The intra observer reliability coefficient was 0.89) and therefore this method was used to detect the onset times of muscle activation.

Dependent Variables

Angular displacement, angular acceleration and three EMG profiles (Biceps, Triceps and Masseter muscles) were recorded for each trial. Angular displacement was used to determine the displacement reaction time, first movement time (for the forearm extension), movement accuracy to the first target and total movement time.

Displacement reaction time was measured as the time from the imperative stimulus to the start of angular displacement about the elbow joint. For the purposes of this study, the start of angular displacement was determined using a computer algorithm. First, displacement data for 200 ms before the imperative stimulus were analyzed and the mean and standard deviation calculated. Second, the data collected following the imperative stimulus were scanned forward until the point where the subjects had moved more than five degrees from the starting position. Data were then scanned backwards until the point where the displacement profile was within the bandwidth of one standard deviation (calculated from data prior to stimulus onset). The start of angular displacement was the next point (1 msec) forward in time from that point.

First movement time (for the forearm extension) was calculated as the time interval between the start of angular displacement and the largest positive value of the angular displacement (the range of the extension movement was from -22.5 degrees to +22.5 degrees). Also, the angular position (measured in degrees) of the largest positive value was used to determine the accuracy of the movement to the first target. The constant error was calculated for each target.

Subjects over-shooting the target received their positional information as the positive difference between the target position and the response cursor, while under-shoots were reported as a negative difference.

Total movement time (for the forearm extension-flexion movements) was the time interval between the start of angular displacement and largest negative value of the angular displacement profile (the range of the flexion movement was from +22.5 degrees to -22.5 degrees).

Through the use of EMG recordings, the premotor and motor components of the reaction time period were determined. Premotor reaction time was calculated by measuring the time interval between the onset of the imperative stimulus and the first sign of heightened electromyographic activity above baseline at the motor point region of the muscle that is principally responsible for initiating the response. Motor reaction time was calculated by measuring the time interval between the first sign of heightened EMG activity above baseline and the initiation of overt movement (as measured by displacement values of the optical encoder).

The angular acceleration profile was used to calculate peak acceleration and time to peak acceleration. Peak acceleration was defined as the absolute largest value of the acceleration profile. Time to peak acceleration was calculated as the time interval between the start of angular acceleration (calculated in the same way as the onset of angular displacement) and the point of peak acceleration.

The angular velocity profile was obtained by integrating the angular acceleration values. It was used to calculate peak velocity and time to peak velocity. Peak velocity was defined as the absolute largest value of the velocity profile. Time to peak velocity was calculated as the time interval between the start of angular velocity (calculated in the same way as the onset of angular displacement) and the point of peak velocity.

Data Analysis

The displacement, acceleration, velocity and EMG profiles of each trial were visually inspected. Following this procedure, detailed results for each trial were obtained through the use of an analysis profile program. These results were then imported into LOTUS 123 (Volume 2.2) for the calculation of means and standard deviations for each individual subject. From these individual data, group means and standard deviations were computed for each of the three movement conditions and each of the seven probe positions (see Appendix A). The data were analyzed using the statistical package SYSTAT 5.0 for Windows.

Statistical Analysis

Separate analyses were performed on the primary and secondary task data. For the primary task analysis, the design was a 2 (2 task conditions: the primary task in the single task condition and the primary task in the dual task condition) X 3 (3 movement conditions: E, EFS and EFL) X 7 (7 probe positions: -150, +100, EMG + 30, PV, PA, END and END + 50) arrangement with repeated measures (RM) on all factors. Each task condition was also subjected separately to a two-way RM ANOVA. RM ANOVA's were performed on the dependent variables displacement, premotor and motor reaction time, first and total movement time, first target accuracy, peak velocity, time to peak velocity, peak acceleration and time to peak acceleration. In order to compare the performance on catch trials to that of the regular trials a 3 (3 trial types: catch, single and dual task trials) X 3 (3 movement conditions) RM ANOVA was performed on the displacement, premotor and motor reaction time data.

For the analysis of the secondary task performance the design was a 4 (4 movement conditions: the secondary task in the single task condition (1 movement condition) and the secondary task in the dual task condition (3

movement conditions)) X 7 (7 probe positions) arrangement with repeated measures on all factors. Again, each task condition was subjected separately to a RM ANOVA. For the secondary task in the single task condition, the design was a one-way RM ANOVA; For the secondary task in the dual task condition, the design was a 3 (3 movement conditions) X 7 (7 probe positions) RM ANOVA. RM ANOVA's were performed on Masseter premotor reaction time data. The performance on catch trials was compared to that of the regular trials by means of a 2 (2 trial types: catch and dual task trials) X 3 (3 movement conditions) RM ANOVA.

A 0.05 level of significance was used throughout the experiment. It is acknowledged that because of the large number of omnibus F-tests, the per experiment Type I error rate is highly inflated. However, in order to maintain adequate power for the tests on each dependent variable, a 0.05 per comparison error rate was maintained. The Huynh-Feldt epsilon factor was used to adjust the degrees of freedom for violation of the sphericity assumption. Post-hoc tests (Tukey's for the main effects and Scheffe's for the interaction effects) were used to analyze any significant differences found between the conditions after the RM ANOVA's.

RESULTS PRIMARY TASK

The primary task in the single task condition

Subjects were instructed to pause for 50-100 msec in the EFS movement condition and the mean pause time was 81 msec (the standard deviation was 14 msec). In the EFL movement condition, subjects were instructed to pause for 250-300 msec and the mean pause time was 261 msec (the standard deviation was 26 msec). As expected, the total movement time was greater overall for EFL than for EFS movements ($F_{1,11}$ = 136.6, $p < .001$; EFL = 915 msec, EFS = 713 msec).

Parallel findings for displacement reaction time (DRT) and premotor reaction time (PMT) were expected because in most experiments in which DRT was fractionated, high correlations were found between DRT and PMT (e.g., Christina & Rose, 1985; Fischman, 1984), although this is not always the case (see Anson, 1982, 1989; Sidaway, 1988). In Figure 2a, b and c, the group means for displacement, premotor and motor reaction time (MOT) are presented (See Appendix A for the means and standard deviations of all dependent variables). The results of a movement condition (3) by probe position (7) repeated measures (RM) ANOVA performed separately on the DRT, PMT and MOT data indicated that the main effect of movement condition was significant for all three dependent measures (see Table 1). A post-hoc Tukey's test (Tukey, 1953) revealed that the DRT, PMT and MOT were significantly shorter for E than for EFS and EFL movements.

For the dependent variables first movement time, peak acceleration, time to peak acceleration, peak velocity, time to peak velocity and first target accuracy, the main effects of movement condition and probe position, as well as the interaction effect failed to reach significance. Thus, it appears that the initial segment of the E, EFS and EFL movements was invariant.

FIGURE 2A: DRT VS. MOVEMENT CONDITION AND PROBE POSITION

FIGURE 2B: PMT VS. MOVEMENT CONDITION AND PROBE POSITION

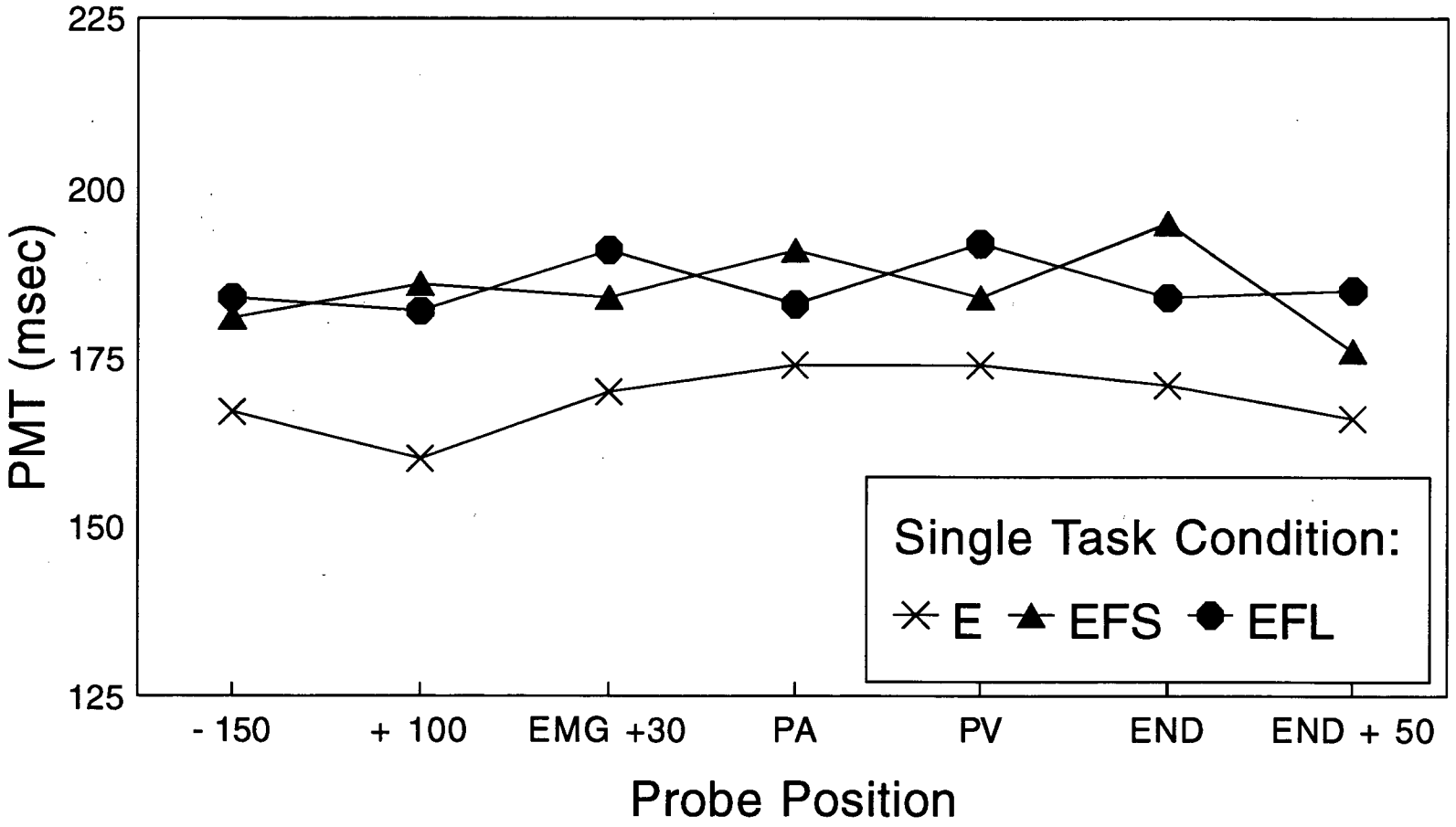


FIGURE 2C: MOT VS. MOVEMENT CONDITION AND PROBE POSITION

Table 1. Summary of ANOVA's for the dependent variables displacement reaction time (DRT), premotor reaction time (PMT) and motor reaction time (MOT) in the single task condition.

Effect	df	F	p (Huynh-Feldt)
Measure - DRT			
Movement Condition	2, 22	8.3	.003
Probe Position	6, 66	1.7	.130
Interaction	12, 132	0.4	.964
Measure - PMT			
Movement Condition	2, 22	4.8	.020
Probe Position	6, 66	1.6	.181
Interaction	12, 132	0.6	.844
Measure - MOT			
Movement Condition	2, 22	4.0	.046
Probe Position	6, 66	0.6	.602
Interaction	12, 132	1.6	.104

The primary task in the dual task condition

The mean pause times for EFS and EFL movements were 84 and 274 msec, respectively (the standard deviations were 8 and 19 msec). Therefore, the total movement time was greater overall for EFL than for EFS movements ($F_{1,11}$ = 150.5, $p < .001$; EFL = 942 msec, EFS = 733 msec).

In Figure 3a, b and c, the group means for DRT, PMT and MOT are presented. A movement condition (3) by probe position (7) RM ANOVA performed separately on the DRT and PMT data revealed a significant main effect of probe position, while the effect of movement condition and the interaction both failed to reach significance (see Table 2). The results of a post-hoc Tukey's test indicated that when the secondary task stimulus occurred 150 msec prior to the primary task stimulus (probe position 1), the DRT and PMT for the primary task were significantly longer than when the secondary task stimulus occurred after the primary task stimulus. As can be seen in Table 2, the effect of movement condition just failed to reach significance. The mean DRT values for E, EFS and EFL movements were 279, 299 and 289 msec.

For the dependent variables motor reaction time, first target accuracy, first movement time, peak acceleration, time to peak acceleration, peak velocity and time to peak velocity, the main effects of movement condition and probe position, as well as the interaction effects failed to reach significance.

A comparison of single and dual task performance

A task condition (2) by movement condition (2) by probe position (7) RM ANOVA, performed separately on the pause time (PT) and total movement time (TMT) data, yielded only one significant effect, that being for movement condition ($F_{1,11}$ = 745.3, $p < .001$ and $F_{1,11}$ = 211.4, $p < .001$, for PT and TMT, respectively).

FIGURE 3A: DRT VS. MOVEMENT CONDITION AND PROBE POSITION

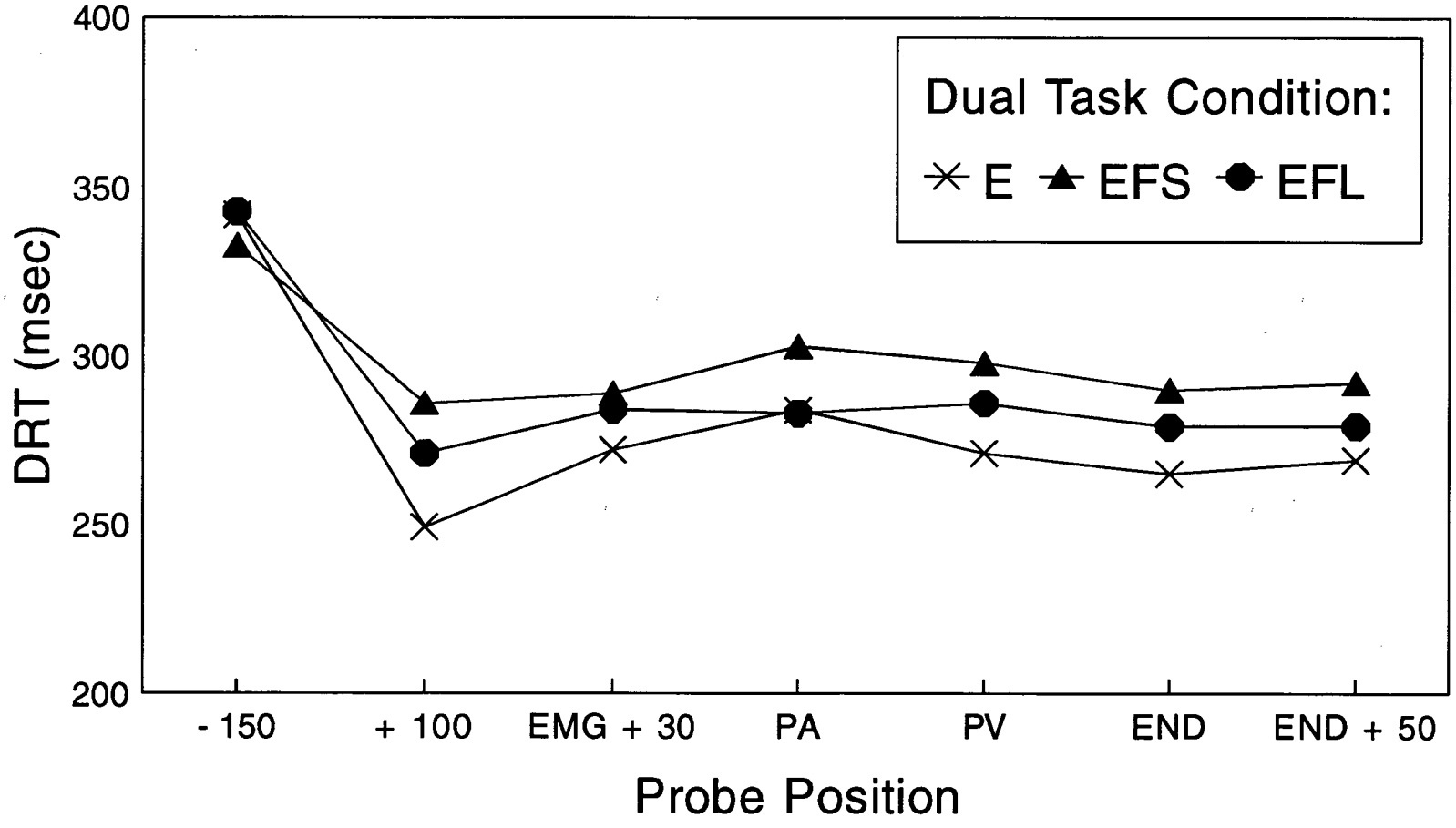


FIGURE 3B: PMT VS. MOVEMENT CONDITION AND PROBE POSITION

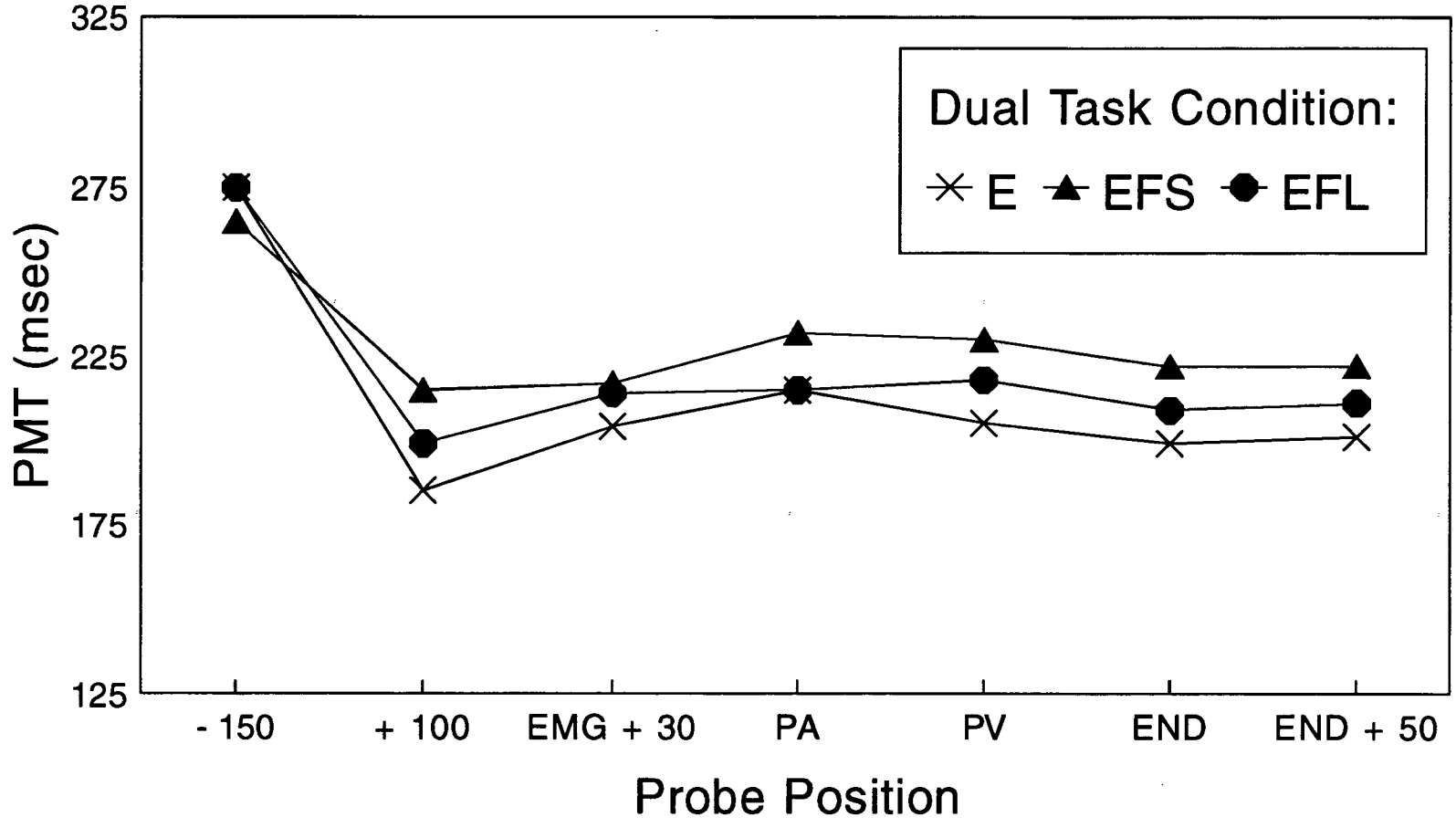


FIGURE 3C: MOT VS. MOVEMENT CONDITION AND PROBE POSITION

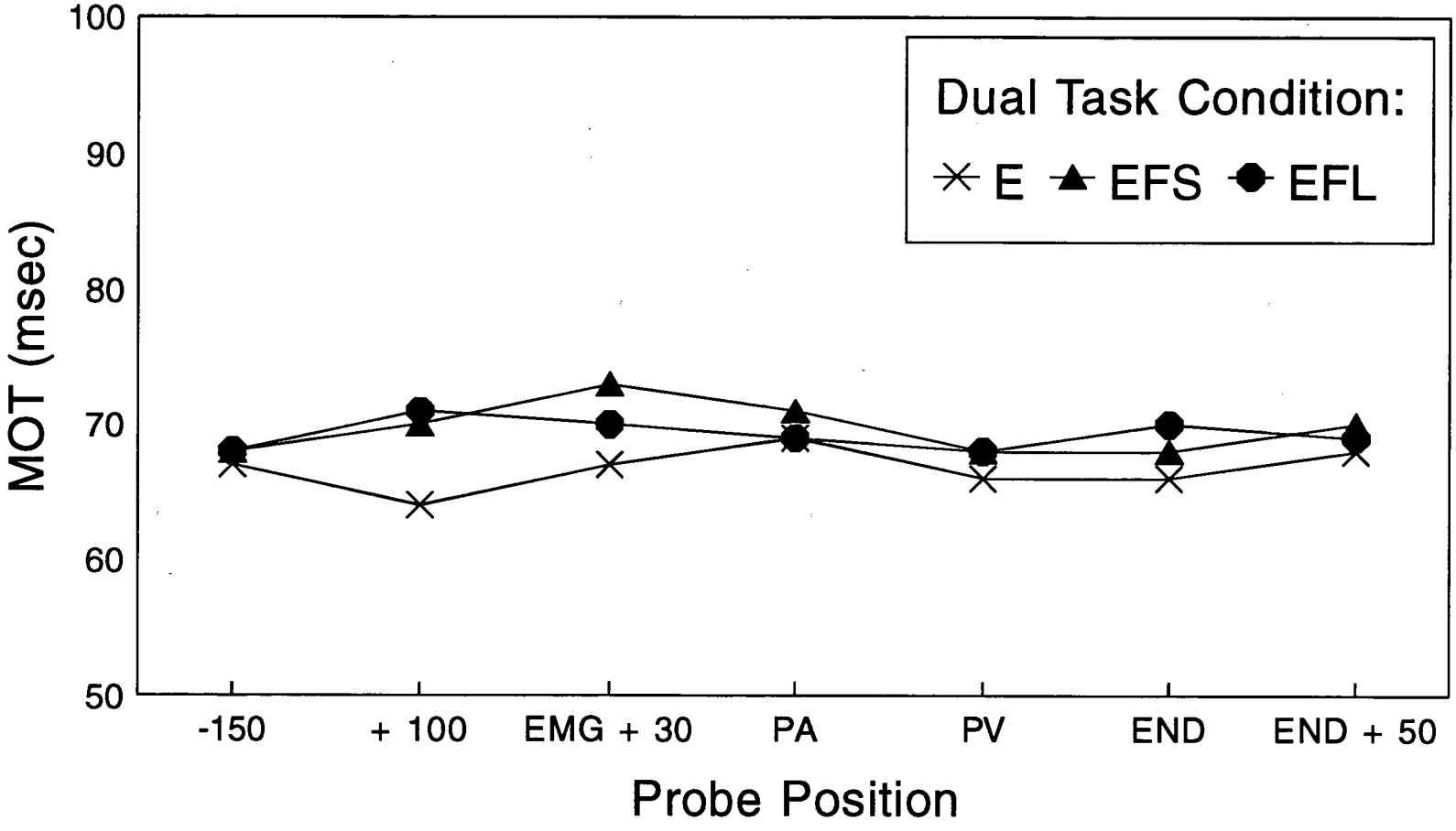


Table 2. Summary of ANOVA's for the dependent variables displacement reaction time (DRT), premotor reaction time (PMT) and motor reaction time (MOT) in the dual task condition.

Effect	df	F	p (Huynh-Feldt)
Measure - DRT			
Movement Condition	2, 22	3.4	.055
Probe Position	6, 66	21.0	< .001
Interaction	12, 132	1.1	.338
Measure - PMT			
Movement Condition	2, 22	3.1	.076
Probe Position	6, 66	21.4	< .001
Interaction	12, 132	0.9	.506
Measure - MOT			
Movement Condition	2, 22	2.0	.163
Probe Position	6, 66	0.9	.518
Interaction	12, 132	0.6	.826

The results of a trial type (3) by movement condition (3) RM ANOVA performed on the DRT and PMT data to compare the mean values for DRT and PMT for the primary task in the single task condition, to those of the primary task in the dual task condition and the 'no tone' catch trials showed a significant main effect of trial type ($F_{2,\ 22}$ = 32.8, Huynh-Feldt $p < .001$ and $F_{2,\ 22}$ = 31.9, Huynh-Feldt $p < .001$, for DRT and PMT, respectively). Table 3 shows the mean values and standard deviations of the latency data for the primary task in the single and dual task condition and 'no tone' catch trials averaged over the three movement conditions. A post-hoc Tukey's test revealed that the DRT and PMT were significantly longer for 'no tone' catch and dual task trials than for single task trials. The MOT was comparable for 'no tone' catch, single and dual task trials.

A task condition (2) by movement condition (3) by probe position (7) RM ANOVA performed separately on the DRT and PMT data showed significant effects of probe position, task condition and the probe position by task condition interaction for both dependent measures (See Table 4). In Figure 4a and b the means from this interaction are presented for DRT and PMT, respectively. The two way and three way interactions failed to reach significance. A post-hoc Tukey's test indicated that when the secondary task stimulus occurred 150 msec prior to the primary task stimulus (probe position 1), the DRT and PMT for the primary task were significantly longer than when the secondary task stimulus occurred after the primary task stimulus. Also, the DRT and PMT were significantly longer for the dual than for the single task condition. However, the nature of the interaction revealed that the differences between the single and dual task conditions at probe positions 2, 3, 4, 5, 6, 7 (26, 34, 40, 35, 26 and 39 msec respectively) were significantly smaller than the difference at probe position 1 (94 msec). For PMT these differences were 24, 30, 38, 35, 27 and 36 msec, for probe positions 2, 3, 4, 5, 6 and 7,

Table 3. Mean values and standard deviations for the dependent variables displacement, premotor and motor reaction time for the primary task in the single and dual task condition and 'no tone' catch trials.

	Primary task in the single task condition	Primary task in the dual task condition	'No tone' catch trials
DRT	247 (39.8)	279 (42.8)	298 (46.1)
PMT	180 (38.6)	212 (42.5)	227 (46.9)
MOT	67 (7.4)	67 (7.8)	71 (11.3)

Table 4. Summary of ANOVA's for the dependent variables displacement reaction time (DRT), premotor reaction time (PMT) and motor reaction time (MOT) for the single vs. dual task condition.

Effect	df	F	p (Huynh-Feldt)
Measure - DRT			
Movement Condition	2, 22	9.1	.001
Probe Position	6, 66	13.2	< .001
Task Condition	1, 11	36.9	< .001
Probe x Task Interaction	6, 66	19.4	< .001
Measure - PMT			
Movement Condition	2, 22	6.9	.005
Probe Position	6, 66	13.5	< .001
Task Condition	1, 11	41.0	< .001
Probe x Task Interaction	6, 66	21.6	< .001
Measure - MOT			
Movement Condition	2, 22	9.1	.003
Probe Position	6, 66	0.4	.891
Task Condition	1, 11	1.3	.274
Probe x Task Interaction	6, 66	1.2	.346

FIGURE 4A: DRT VS. TASK CONDITION AND PROBE POSITION

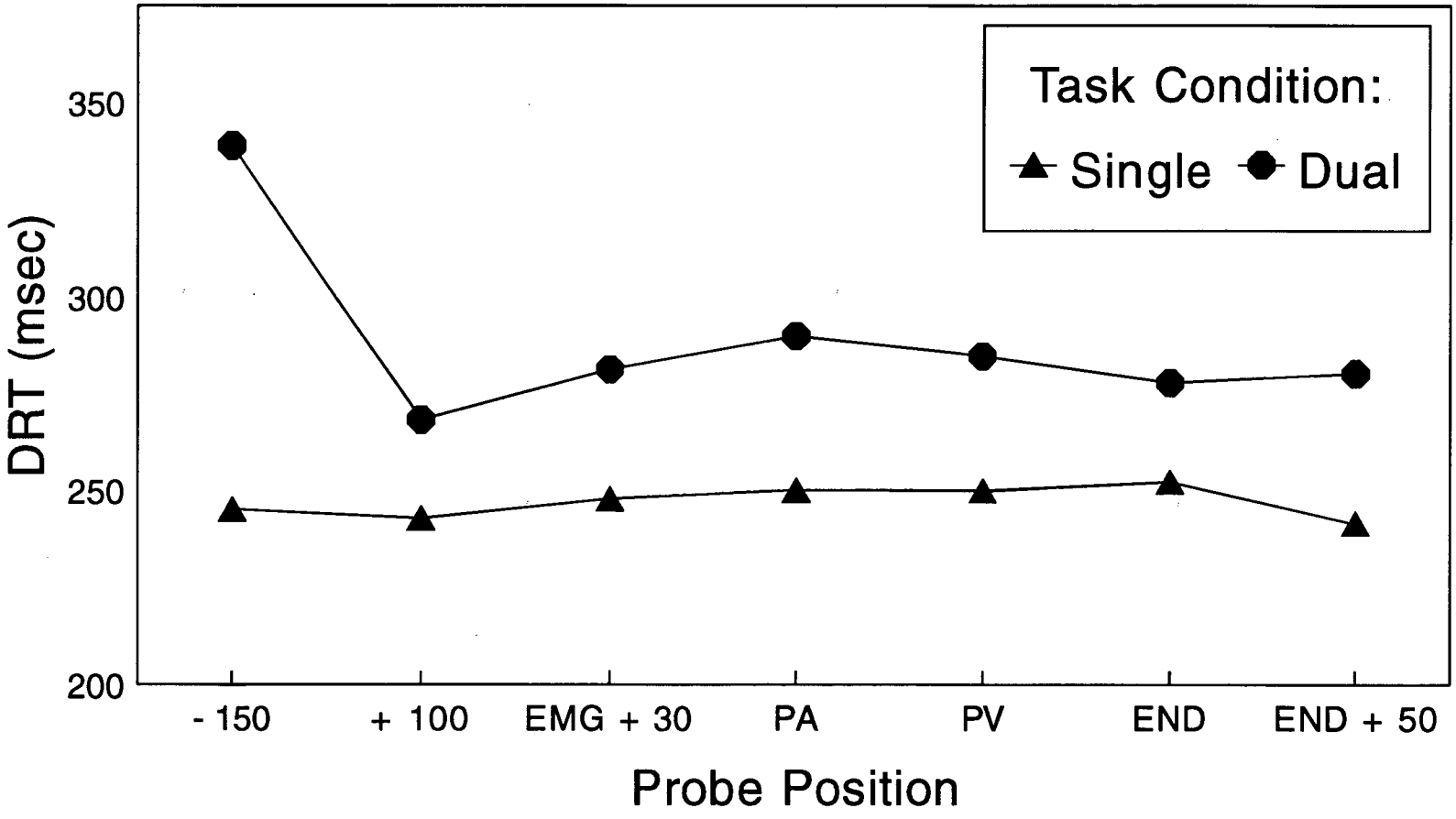
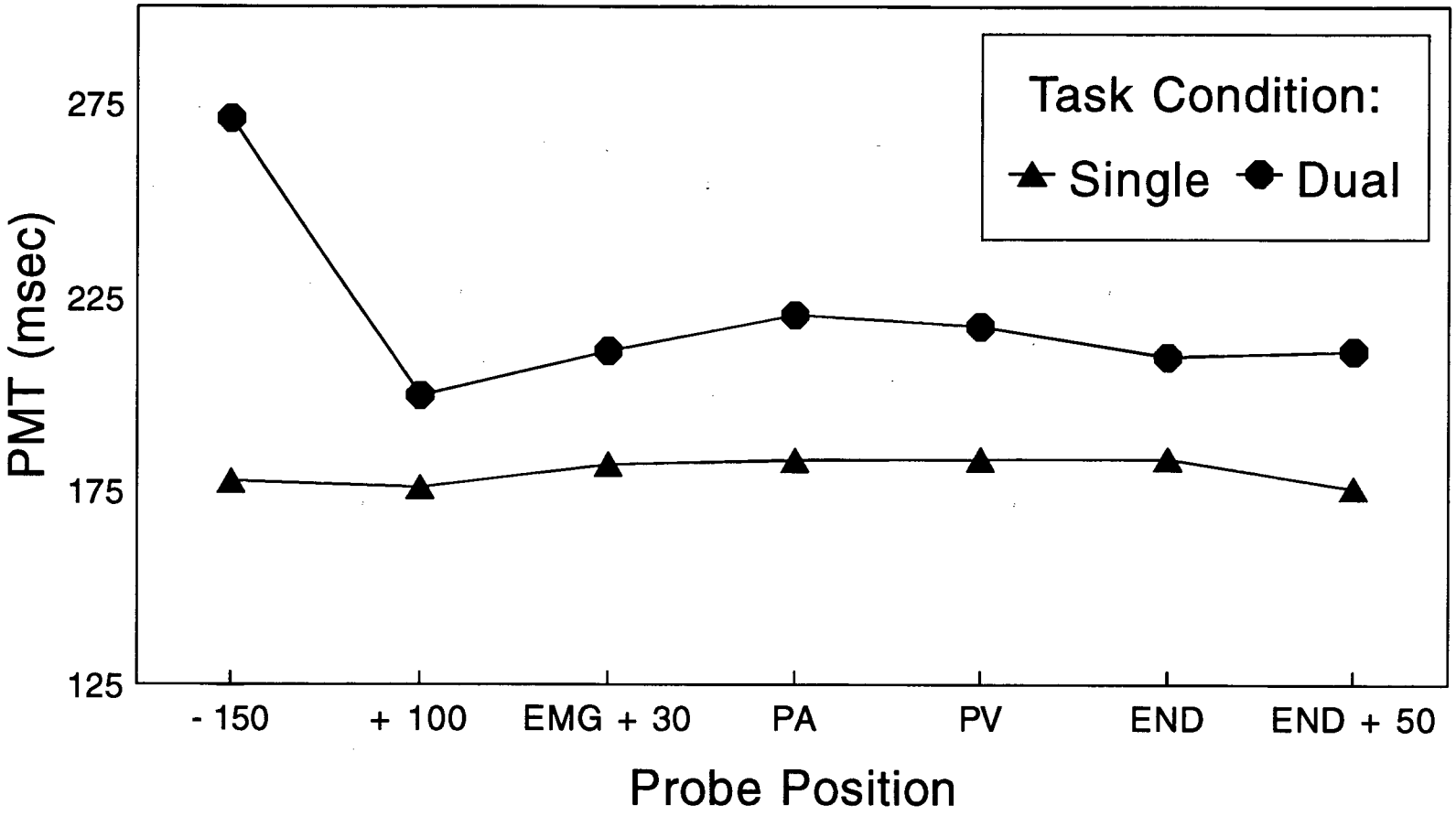


FIGURE 4B: PMT VS. TASK CONDITION AND PROBE POSITION



respectively and 94 msec at probe position 1.

The results of a task condition (2) by movement condition (3) by probe position (7) RM ANOVA performed on motor reaction time, first target accuracy, first movement time, peak acceleration, time to peak acceleration, peak velocity and time to peak velocity indicated that the main effects of movement condition, probe position and task condition, as well as the two and three way interaction effects between these variables failed to reach significance.

DISCUSSION PRIMARY TASK

Pause Time Results

The time between successive extension and flexion movements was manipulated in the present study because findings from previous studies (Franks, Ketelaars, & Nagelkerke, 1992; Ketelaars, Franks, & Nagelkerke, 1993, Appendix C) have indicated that this pause time duration appears to have an impact on whether sequences of forearm movements are preprogrammed or programmed on-line. Subjects in the present study were instructed to perform extension movements and extension-flexion movements that required a short or a long pause time (50-100 msec or 250-300 msec). It was expected therefore that the pause time instructions would be responsible for significant differences between EFS and EFL movements.

The results of the statistical analyses performed on the pause time and total movement time data indicated that, as expected, the only significant difference that was detected for the primary task in the single and dual task conditions was that the pause time and total movement time were significantly longer for the EFL than for the EFS movement. This was also found when single task performance was compared to dual task performance. Because of the failure to detect significant main effects of task condition, probe position or an interaction effect between any of these variables, it can be concluded that

the mean values for pause time and total movement time for both the EFS and EFL movements were comparable in the single and dual task condition and for the seven probe positions.

Displacement and Premotor Reaction Time Results

McLeod's (1977) parallel-processing theory may account for the finding that the displacement and premotor reaction times were significantly longer for 'no tone' catch and dual task trials than for single task trials. According to McLeod (1977), in experiments where the foreperiod and the interval between two separate stimuli are varied, subjects adopt a strategy whereby they devote a fixed proportion (less than the maximum available) of their limited attentional capacity to the primary task stimulus, irrespective of the arrival time of the secondary task stimulus. On the basis of this theory, McLeod (1977) predicted that the displacement reaction time for catch trials in which the secondary task stimulus does not appear would be the same as for dual task trials. McLeod (1977) also predicted that the displacement reaction time in the dual task condition would be longer than the displacement reaction time in the single task condition, because the subjects know there will be no secondary task stimulus in the single task condition. The subjects could therefore allocate full capacity to the primary task stimulus (McLeod, 1977, p 388). Several other studies have also found support for this parallel-processing theory (e.g., Franks & Canil, 1985, 1987).

Findings from several previous studies have indicated that subjects preprogrammed forearm extension movements and extension-flexion movements that required a short pause time (50 - 100 msec) between successive extension and flexion movements (Franks, Ketelaars, & Nagelkerke, 1992; Ketelaars, Franks, & Nagelkerke, 1993, Appendix C). When this pause time exceeded 200 msec, subjects were able to program part of the flexion

movement (or maybe the total flexion movement) during the execution of the extension movement and / or during the pause time. It was expected that these findings would be replicated when the primary task was performed in the single task condition in the present experiment, with pause times being 81 and 261 msec for the EFS and EFL movements, respectively. However, this was not the case. The main finding for the primary task in the single task condition was that the displacement and premotor reaction times were significantly shorter for E than for EFS and EFL movements and comparable for EFS and EFL movements. Thus, these findings suggested that subjects preprogrammed not only the EFS but also the EFL movements.

It is not clear why the findings of previous studies were not replicated when the primary task was performed in the single task condition. The experimental procedure and the design of this study was comparable to that of previous experiments, with two exceptions. That is, in the single task condition of the present experiment, subjects were presented with a stimulus for the jaw clench response in addition to the stimulus for the arm movement response that was used in previous experiments. They were instructed not to react to the jaw clench stimulus. Furthermore, the design of the present experiment was such that all subjects were tested on two consecutive days and on both days they performed the primary task in the single and dual task condition. Since the order of these task conditions was counterbalanced, subjects had experienced responding to the jaw clench stimulus in the dual task condition prior to being tested in the single task condition. Because subjects were required to react to the jaw clench stimulus in the dual task condition, they may have experienced some difficulties in withholding this particular response when its stimulus occurred in the single task condition. In order to avoid any potential interfering effects of the secondary task stimulus to on-line programming of the forearm movements, subjects may have adopted a

strategy whereby they preprogrammed both the EFS and EFL movements.

When the primary task was performed in the dual task condition, the displacement and premotor reaction times were comparable for E, EFS and EFL movements, suggesting that subjects were able to program both EFS and EFL movements on-line in this particular condition. It should be mentioned here that, as was found previously (Franks, Ketelaars, & Nagelkerke, 1992; Ketelaars, Franks, & Nagelkerke, 1993, Appendix C) the displacement and premotor reaction times were 20 msec longer for the EFS than for the E movement, suggesting that EFS movements were preprogrammed. However, in the present experiment this difference just failed to achieve the 0.05 level of significance.

The finding that the displacement and premotor reaction times were significantly longer for the primary task in the dual than in the single task condition was unexpected, yet several studies have reported similar findings (e.g., Smith, 1969, 1967; Noble, Sanders, & Trumbo, 1981). Navon and Gopher (1979) introduced the term 'concurrence costs' to explain the delay of displacement reaction time when subjects carry out two tasks at the same time or in fairly close succession. Concurrence costs refer to the possibility that "maximal performance in single task situations is higher than what can be extrapolated about performance in the same task conjoined with the worst level of performance of the other task, because the mere act of adding a second task will withhold from the first one more resources than required by the new one" (Navon & Gopher, 1979, p. 224). Thus, the delay in displacement and premotor reaction time for the primary task in the dual task condition may have occurred because of the reduced availability of limited resources in this condition.

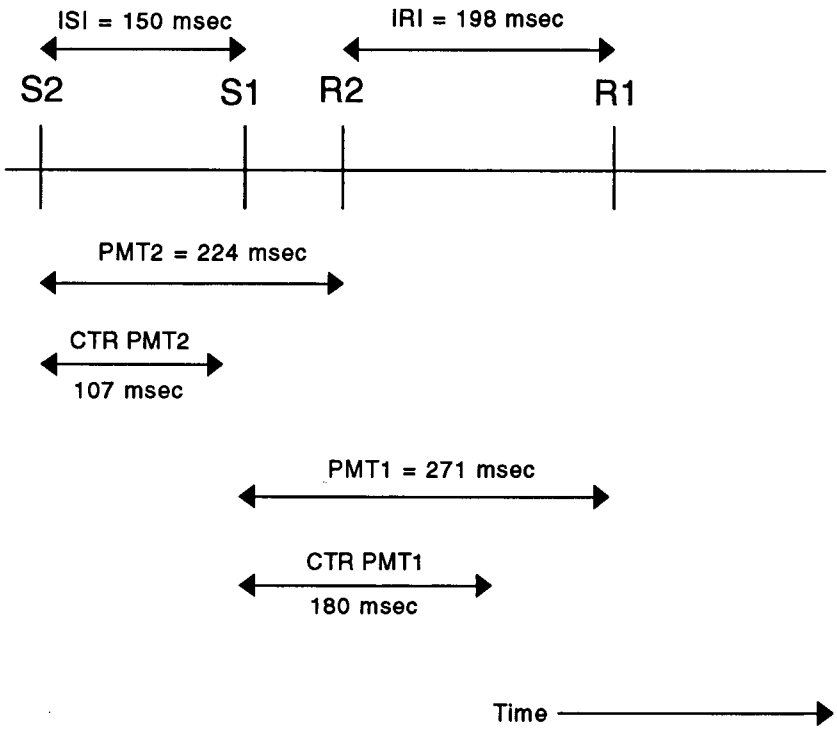
When subjects performed the primary task in the dual task condition, they were instructed to make the movement response as fast and accurately as

possible. They were also advised to respond to the secondary task stimulus as fast as possible, but to consider the movement task of primary importance. Given these instructions, the processing demands of the primary task should have been afforded priority over those of the secondary task (Abernethy, 1988). Consequently, the displacement and premotor reaction time results for the primary task should have been uninfluenced by the occurrence of the secondary task stimulus. However, the results for the primary task in the dual task condition showed that when the secondary task stimulus occurred 150 msec prior to the primary task stimulus (probe position 1), the displacement and premotor reaction times for the primary task were significantly longer than when the secondary task stimulus occurred after the primary task stimulus.

There is a considerable body of evidence to suggest that the slowing of the primary task response at probe position 1 occurred because of the psychological refractory period (PRP) effect. The PRP effect refers to the finding that when people respond to each of two successive stimuli, the response to the second stimulus becomes slower when the time interval between the two stimuli is reduced. Telford (1931) was the first to discover this phenomenon and the PRP effect has since been observed in a great variety of different tasks, including simple reaction time (e.g., Telford, 1931) and choice reaction time tasks (e.g., Creamer, 1963) tasks. Most of the earliest PRP experiments involved two manual responses, sometimes with the same finger and sometimes with different fingers (e.g., Vince, 1949). However, recent work shows that a PRP effect can be found when pairs of tasks use very diverse kinds of responses. Examples include manual and eye movement responses (Pashler, Carrier, & Hoffman, 1993), manual and vocal responses (Pashler, 1990) and manual and foot responses (Osman & Moore, 1993).

In Figure 5 an overview is given of the events that took place when the secondary task stimulus (S2) occurred 150 msec prior to the primary task

Figure 5 A demonstration of psychological refractoriness



stimulus (S1). From the data it can be calculated that the premotor reaction time to S2 was 224 msec, whereas the average premotor reaction time for the secondary task in the single task condition (i.e., CTR PMT2) was 107 msec (See Table 28 and 29 in Appendix A for an overview of the Masseter premotor reaction times for the secondary task in the single and dual task conditions). The premotor reaction time to S1 was 271 msec and the average premotor reaction time for the primary task in the single task condition (i.e., CTR PMT1) was 180 msec (See Table 8 and 9 in Appendix A for an overview of the premotor reaction times for the primary task in the single and dual task conditions). Thus, in the dual task condition, the response to the primary and secondary task stimuli were slowed compared to the corresponding latencies when the same tasks were performed in the single task condition. The slowing that occurred for the primary task is comparable to the slowing that was observed in several other PRP studies (e.g., Karlin & Kestenbaum, 1968; Franks & Canil, 1985).

A number of accounts of slowing of the second response have been proposed. According to the postponement theory (e.g., Smith, 1969; Welford, 1952), certain processes required to perform reaction time tasks constitute a single-channel bottleneck and only one task can gain access to these processes at any time. While the first task is occupying the bottleneck processes, any stage of the second task that requires these same processes must be postponed and such postponement is the cause of the slowing of the second response. Postponement theorists disagree on the issue of where the bottleneck is located. Some (e.g., Pashler, 1984; Pashler & Johnston, 1989; Smith, 1969; Welford, 1952) argue that the bottleneck occurs at or before the level of central processes associated with decision making, response selection, or both. Others (e.g., Keele, 1973; Logan & Burkell, 1986; Norman & Shallice, 1986) claim that there is no bottleneck prior to actual initiation of responses. In their view,

response selection on the second task occurs in parallel with processing on the first task and only the actual execution of the response is subject to postponement.

Capacity theorists (e.g., Kahneman, 1973; McLeod, 1977) offer another account of slowing of the second response. Both tasks are assumed to draw on a central pool of attentional capacity. At long inter-stimulus intervals (ISI's), the first task is completed before the second task begins, so that each task has access to the entire pool. At short ISI's, however, the demands of the two task overlap. Because the capacity allocated to the second task is reduced under these conditions, the rate of processing on the second task slows down and thus the reaction time to the second task slows down.

Motor Reaction Time Results

It was expected that the motor reaction times would be comparable for E, EFS and EFL movements, because the initial segment of each movement response was invariant [i.e., no significant main effects or interaction effects were found between movement conditions for the dependent variables first movement time, peak acceleration, time to peak acceleration, peak velocity, time to peak velocity and first target accuracy]. However, the motor reaction time was shorter for E than for EFS and EFL movements. Several other researchers have also reported increases in motor reaction time with increases in response complexity, but have failed to explain what caused this motor reaction time increase. Specifically, in an experiment in which subjects were required to tap a single target, or a series of circular targets as rapidly as possible with a hand-held stylus, Sidaway (1991) found that the mean motor reaction time for the one-tap condition was significantly shorter than the motor reaction time of the two- and three-tap conditions. Sidaway (1991) maintained that although the ANOVA indicated that there was a statistically significant main effect for the

number of response elements, "the magnitudes of the motor reaction time differences between the conditions were very small" (p. 126), thereby implying that these motor reaction time differences were not meaningful differences in terms of human information processing. Similarly, Fischman (1984) found that when subjects had to contact from one to five targets, the motor reaction time for the one target condition was less than the motor reaction time for the three, four and five target conditions. Fischman (1984) stated that: "The difference in mean motor reaction time across all five target conditions was only 4 msec. Although statistically significant, this difference is far too small to account for the substantial simple reaction time effect; hence the simple reaction time effect is a central effect" (p. 415).

Van Donkelaar and Franks (1991a) have expressed some concern with regards to the usefulness of the motor reaction time measure. They indicated that the traditional view on motor reaction time, in which motor reaction time is believed to reflect the duration of non programming events [e.g., electromechanical delay and development of sufficient torque to initiate movement (Anson, 1982)] is limited. Van Donkelaar and Franks argued that if it is assumed that movements can be programmed at any time before or during the execution of a movement sequence, then it cannot be denied that this programming also occurs during the motor reaction time period. Similarly, if it is assumed that entire movement sequences are programmed prior to their initiation, then it seems faulty to assume that as soon as the muscles become active, this programming can no longer occur. Thus, when Van Donkelaar and Franks found an increase in motor reaction time with an increase in response complexity, they explained this by suggesting that some movement preparation may have occurred during the motor reaction time period. The results of the present experiment appear to substantiate their claim.

Does the secondary task affect primary task performance ?

The main purpose of the primary task analyses was to test for effects of the secondary task on the primary task. It is generally assumed in probe reaction time studies that secondary task reaction times may be interpreted as a measure of the processing demands of the primary task movement conditions if the secondary task shows little or no effect on primary task performance (e.g., Kerr, 1975; Abernethy, 1988). According to Kerr (1975) three conditions should be checked. First, scores on the primary task in the dual task condition should equal scores on the primary task in the single task condition. This was not the case in the present experiment, because the displacement and premotor reaction times were significantly longer for the primary task in the dual than in the single task condition. However, it appeared that the three primary task movement conditions were affected to the same extent, because no significant interaction was found between task condition and movement condition. A second condition to be checked is that specific secondary task stimulus positions should not influence the primary task differentially. The findings of the present experiment indicated that the displacement and premotor reaction times for the primary task in the dual task condition were lengthened when the secondary task stimulus occurred 150 msec prior to the primary task stimulus. Presumably, this delay in displacement and premotor reaction time was due to the psychological refractory period effect. The more important finding was that when the secondary task stimulus occurred after the primary task stimulus, no significant effect of probe position was found. In addition, no significant main effect of probe position was found for the primary task in the single task condition. Third, when secondary task reaction times for different primary task conditions are compared, one must consider whether or not the secondary task influences the primary task movement conditions differentially. This was not the case because in the present study no

significant interactions were found between probe position and the primary task movement conditions. Taken together, the results of the present experiment suggest that performing the secondary task did alter primary task performance. However, as indicated by the non-significant movement condition by task condition interaction for displacement and premotor reaction time, the secondary task affected all three primary task movement conditions to the same extent. Therefore, the secondary task reaction times may be interpreted as a measure of the processing demands of the primary task movement conditions.

A stronger argument for the assumption that the processing demands of the primary task movement conditions are indeed reflected in the reaction times to the secondary task will be given in the secondary task discussion (see below). It will be argued that responses of the Masseter muscle were delayed at several probe positions because the flexion movement of the EFS and EFL movements was programmed on-line (as evidenced by EMG activity of the Biceps muscle (prime mover of forearm flexion)).

RESULTS SECONDARY TASK

The secondary task in the single task condition

In Figure 6 the group means are presented for the premotor reaction times of the Masseter muscle (MRT) in the single task condition. The results of a one-way RM ANOVA indicated that the MRT's were not significantly different for the seven probe positions (see Table 5).

The secondary task in the dual task condition

Figure 6 also shows the group means for MRT for the three movement conditions in the dual task condition. A movement condition (3) by probe position (7) RM ANOVA revealed a significant effect of probe position and the interaction between probe position and movement condition (see Table 5). The results of a post-hoc Tukey's test showed that the MRT was significantly longer when the secondary task stimulus occurred 150 msec prior to, or 100 msec after the onset of the primary task stimulus, than when the secondary task stimulus occurred at the point at which peak velocity was obtained. A Scheffé's test (Scheffé, 1953), used to examine the interaction effect, indicated that the differences in MRT between E and EFL movements at probe positions 3 and 4 (5 and 7 msec, respectively) were significantly smaller than the difference at probe position 6 (86 msec).

A comparison of single and dual task performance

Mean values for 'no movement' catch trials for the three movement conditions are presented in Figure 6. The results of a trial type (2) by movement condition (3) RM ANOVA performed on the MRT data to compare the mean values for MRT for the secondary task in the dual task condition to those of the 'no movement' catch trials showed a significant main effect of trial type [$F_{1,\ 11}$ = 15.6, p = .002]. This significant trial type effect was due to the longer MRT for

FIGURE 6: MRT VS. MOVEMENT CONDITION AND PROBE POSITION

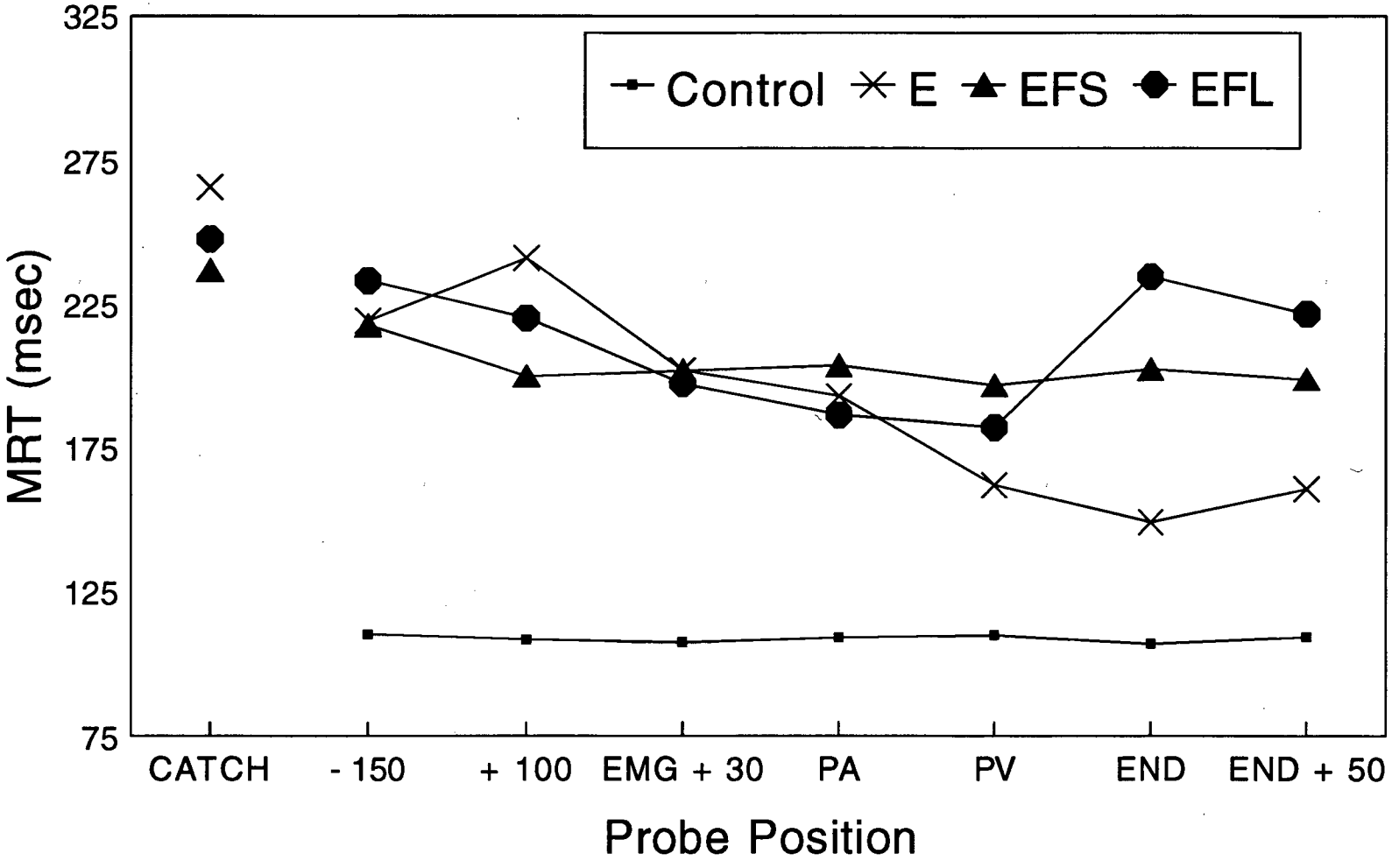


Table 5. Summary of ANOVA's for the dependent variable Masseter premotor reaction time (MRT) in the single, dual and single vs. dual task conditions.

Effect	df	F	p (Huynh-Feldt)
MRT- Single task condition			
Probe Position	6, 66	0.4	.884
MRT - Dual task condition			
Movement Condition	2, 22	2.1	.162
Probe Position	6, 66	4.5	.002
Interaction	12, 132	3.4	.011
MRT - Single vs. Dual			
Movement Condition	3, 33	37.3	< .001
Probe Position	6, 66	4.5	.009
Interaction	18, 198	3.5	.008

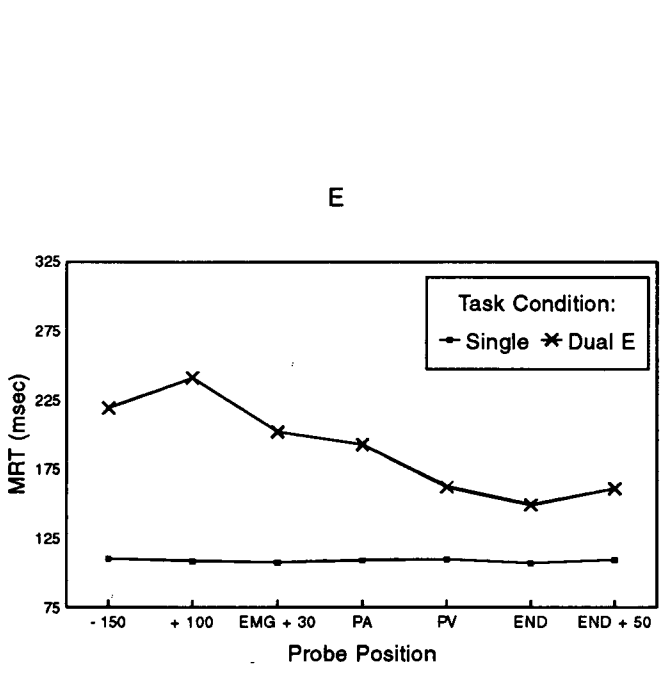
'no movement' catch trials compared to dual task trials.

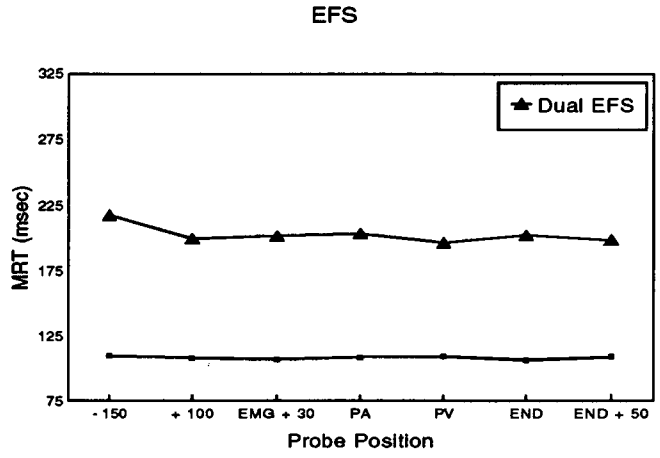
In addition to the effects reported for the secondary task in the dual task condition, a movement condition (4) by probe position (7) RM ANOVA also revealed significant main effects for movement condition and the interaction between movement condition and probe position (see Table 5). The results of a post-hoc Tukey's test indicated that the MRT was significantly faster for the secondary task in the single task condition than for the three movement conditions in the dual task condition. A Scheffé's test indicated that the differences in MRT between the secondary task in the single task condition and the E movement in the dual task condition at probe positions 5, 6 and 7 (53, 43 and 54 msec respectively) were significantly smaller than the difference at probe position 2 (135 msec).

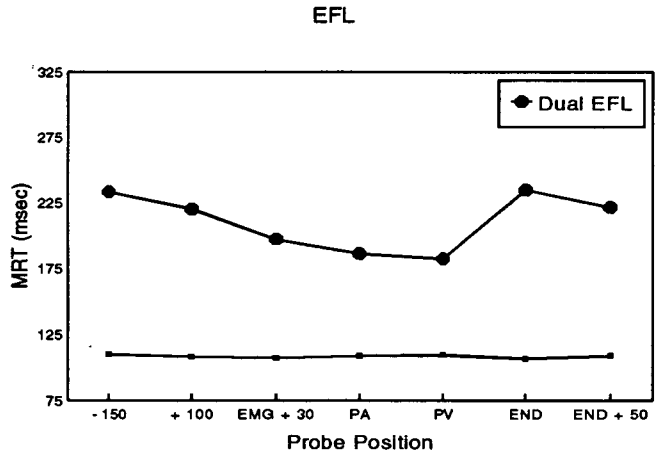
Description of the Masseter Premotor Reaction Time Profiles

In Figure 7 the mean MRT's are presented for the secondary task in the single task condition and for the extension movement in the dual task condition. It is evident that the MRT was increased when the probe occurred during the premotor reaction time period and then subsequently decreased as the probes occurred during the motor reaction time period and at several positions during the execution of the extension movement. For the EFS movement, the MRT's were similar across all seven probe positions (see Figure 7), whereas the MRT profile for the EFL movement reflected an interesting trend. It can be seen in Figure 7 that the MRT was increased for EFL movements when the probe occurred during the premotor reaction time period but decreased when the probes occurred during the motor reaction time period and at the times at which peak acceleration and peak velocity were obtained. The MRT's subsequently increased when the probes occurred at the end of the extension movement and during the pause time.

Figure 7: MRT profiles for E, EFS, and EFL movements







DISCUSSION SECONDARY TASK

In the present experiment the mean premotor reaction times of the Masseter muscle were increased for catch trials. Moreover, the increase was greater than it was for trials in which the primary task stimulus was also presented. Poulton (1950) introduced the term 'unprepared period' to explain this delay in reaction time to the secondary task stimulus for catch and dual task trials (see also Gottsdanker, 1979). According to Poulton, the delay occurred because the secondary task stimulus was presented when subjects were prepared for the primary task stimulus, hence the arm movement may have been inhibited before the jaw clench response could be initiated.

It is not clear why the MRT was longer for catch than for dual task trials. The procedures followed for both types of trials were identical, with one exception. In the case of a catch trial, the secondary task stimulus occurred 1500-2500 msec after the warning signal; For dual task trials, the secondary task stimulus was presented 150 msec prior to the primary task stimulus, which in turn occurred after the same variable foreperiod. Therefore, the average time between the warning signal and the stimulus was longer for catch, than for dual task trials. There is a considerable body of evidence to suggest that simple reaction time increases with the subject's uncertainty about the temporal onset of a stimulus. Generally, the longer the mean foreperiod, the more uncertain the subject is about the time of occurrence of a stimulus, thus the longer the reaction time (e.g., Klemmer, 1956). Therefore, the longer MRT could have been due to the longer average foreperiod duration for catch trials. However, we cannot produce quantitative evidence that this was indeed the reason, as the length of the foreperiod for each trial was not recorded in this experiment. Another explanation for the above findings is that the lengthening of MRT occurred because subjects had to inhibit the arm movement response in the case of a catch trial. It has been found that when a

regularly occurring stimulus is omitted, there is a marked evoked potential for the omitted event (Picton, Hillyard, & Galambos, 1972). This would suggest that the MRT was lengthened because some processing time was required to inhibit the arm movement response. Alternatively, the MRT could have been shortened for dual task trials because the primary task stimulus may have facilitated the response to the secondary task stimulus.

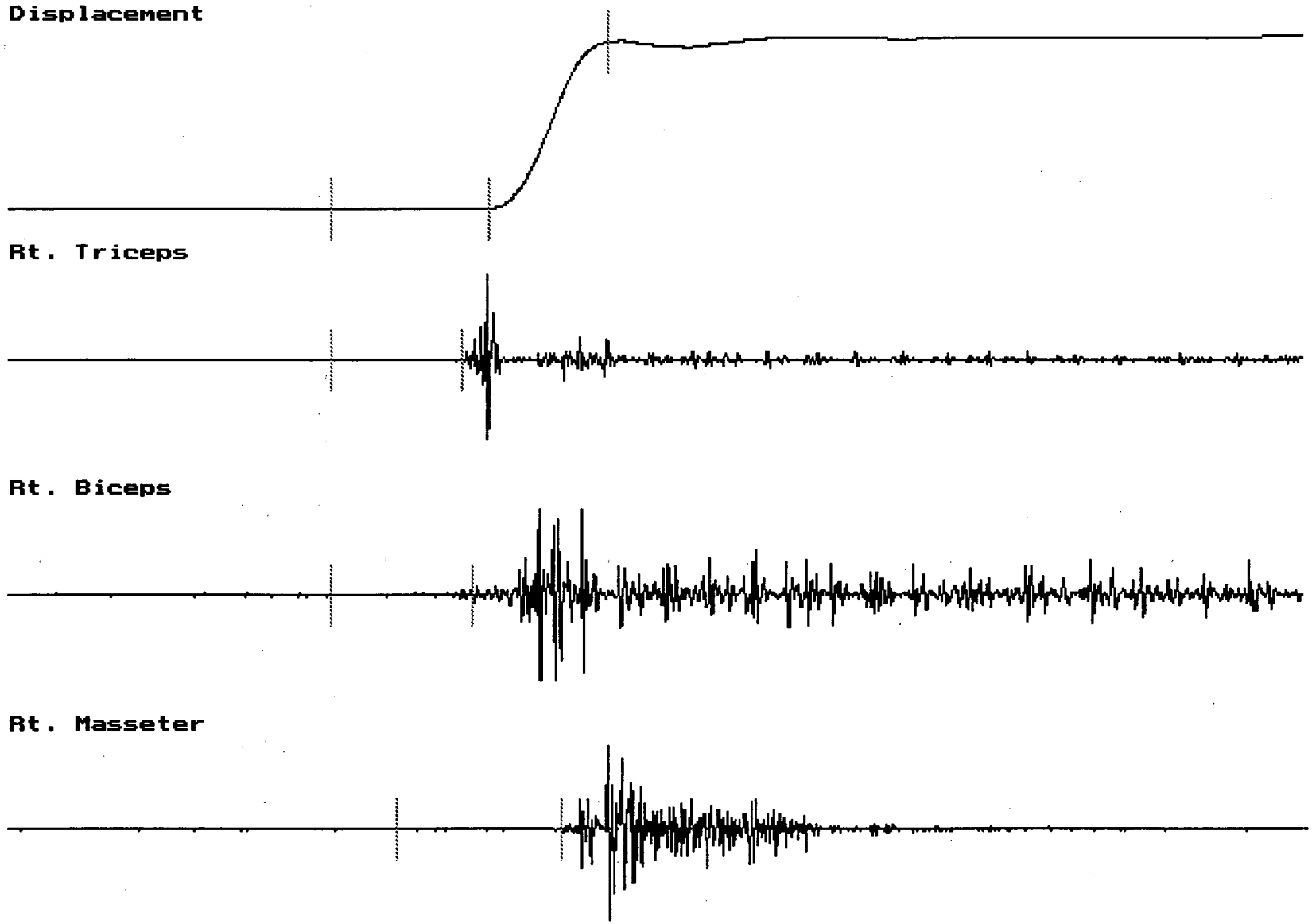
One of the findings of the present study was that the MRT's for all three primary task movement conditions in the dual task condition were consistently higher than the corresponding values for the control condition in which subjects were required to react to the secondary task stimulus without performing the arm movement response. This finding is consistent with the findings of previous probe reaction time studies (Posner & Keele, 1969; Ells, 1973; Kerr, 1975; Salmoni, Sullivan, & Starkes, 1976; Wilke & Vaughn, 1976; Newell & Hoshizaki, 1980; Williams & Sullivan, 1986) and it indicates that some processing capacity is being allocated to the control of the arm movement response. The main interest of the present study however, is not in the absolute attentional demands of movement sequences, but in the differential processing demands of forearm extension as compared to extension-flexion movements. Therefore, it would be more meaningful to compare the MRT profiles of the three movement conditions to each other, rather than to the control condition.

Are movement sequences programmed prior to or after the imperative stimulus in a simple reaction time paradigm ? The results of the present study indicate that the mean MRT's were elevated for E, EFS and EFL movements when a probe occurred prior to the primary task stimulus (i.e., at probe position 1). Therefore, it can be concluded that some aspects of the movement sequence were indeed programmed prior to the imperative stimulus. It appears, however, that movement programming also occurred at various

positions before the initiation of the extension movement, because the mean premotor reaction times of the Masseter muscle were also elevated for E, EFS and EFL movements when a probe occurred during the premotor and motor reaction time period (i.e., at probe positions 2 and 3) of the extension movement. Furthermore, it will be argued in the remainder of the discussion that forearm movements can also be programmed after the initiation of the extension movement, as the premotor reaction times of the Masseter muscle were delayed for EFS and EFL movements when a probe occurred at several positions during the execution of the extension movement (i.e., at probe positions 5, 6 and 7). Thus, the findings of the present study suggest that the programming of movement sequences may be distributed, not only throughout the movement, but also prior to both the warning signal and the imperative stimulus.

A main finding of the present experiment was that the differences in MRT between the secondary task in the single task condition and the extension movement in the dual task condition were significantly larger when the probe occurred during the premotor reaction time period (i.e., probe position 2) than when the probe occurred at the point of peak velocity and at the end, or 50 msec after the end of the extension movement (i.e., probe positions 5, 6 and 7). It is suggested that the MRT was increased at probe position 2 for the extension movement in the dual task condition because of the PRP effect. This phenomenon was described earlier to account for the delay of the arm movement response at probe position 1. In order to establish if the PRP effect could indeed account for the data that were obtained for the extension movement at probe position 2, the differences between the onset times of the Triceps and Masseter muscle (i.e., interresponse intervals, IRI's) were calculated for all trials. Figure 8 shows a displacement profile and the EMG profiles for the Triceps, Biceps and Masseter muscles for one trial for which the

Figure 8: Typical data for an E movement with probe occurring at position 2



probe occurred during the premotor reaction time period of the extension movement in the dual task condition. The temporal location of the primary task stimulus is indicated by a vertical line on the displacement, Triceps and Biceps EMG profiles, whereas the vertical line on the Masseter EMG profile represents the temporal location of the secondary task stimulus. The start of angular displacement and the onset of muscle activity are indicated by a second vertical line on the respective profiles. Because the probe occurred 100 msec after the onset of the primary task stimulus, the IRI was 155 msec for this specific trial. Figure 9 shows a frequency distribution of the IRI's for all trials for which the probe occurred at position 2 for the extension movement in the dual task condition. It is evident that for the majority of the trials, the Masseter response occurred 150 or 225 msec after the initiation of the Triceps response. The PRP effect may account for the slowing of the Masseter response in the following way. Figure 10a shows a schematized stage model of a PRP paradigm in which the response programming stage occupies a 'single channel' (i.e., bottleneck), whereas the other stages in both tasks can overlap without restrictions. It is suggested that while the first task is occupying these bottleneck processes, any stage of the second task that requires these same processes must be postponed and such postponement is responsible for the slowing of the second response (e.g., Pashler, 1984; Pashler & Johnston, 1989). Thus, the Masseter response may have been delayed at probe position 2 for the extension movement in the dual task condition because this response could only be programmed after the programming of the arm movement response had been completed.

Figure 9 also shows a frequency distribution of the IRI's for all trials for which the probe occurred at position 2 for the EFS and EFL movements in the dual task condition. It is evident that the Masseter response was initiated 25 msec after the initiation of the Triceps response for the majority of the trials in

Figure 9: Distribution of interresponse intervals for E, EFS and EFL movements at probe position 2

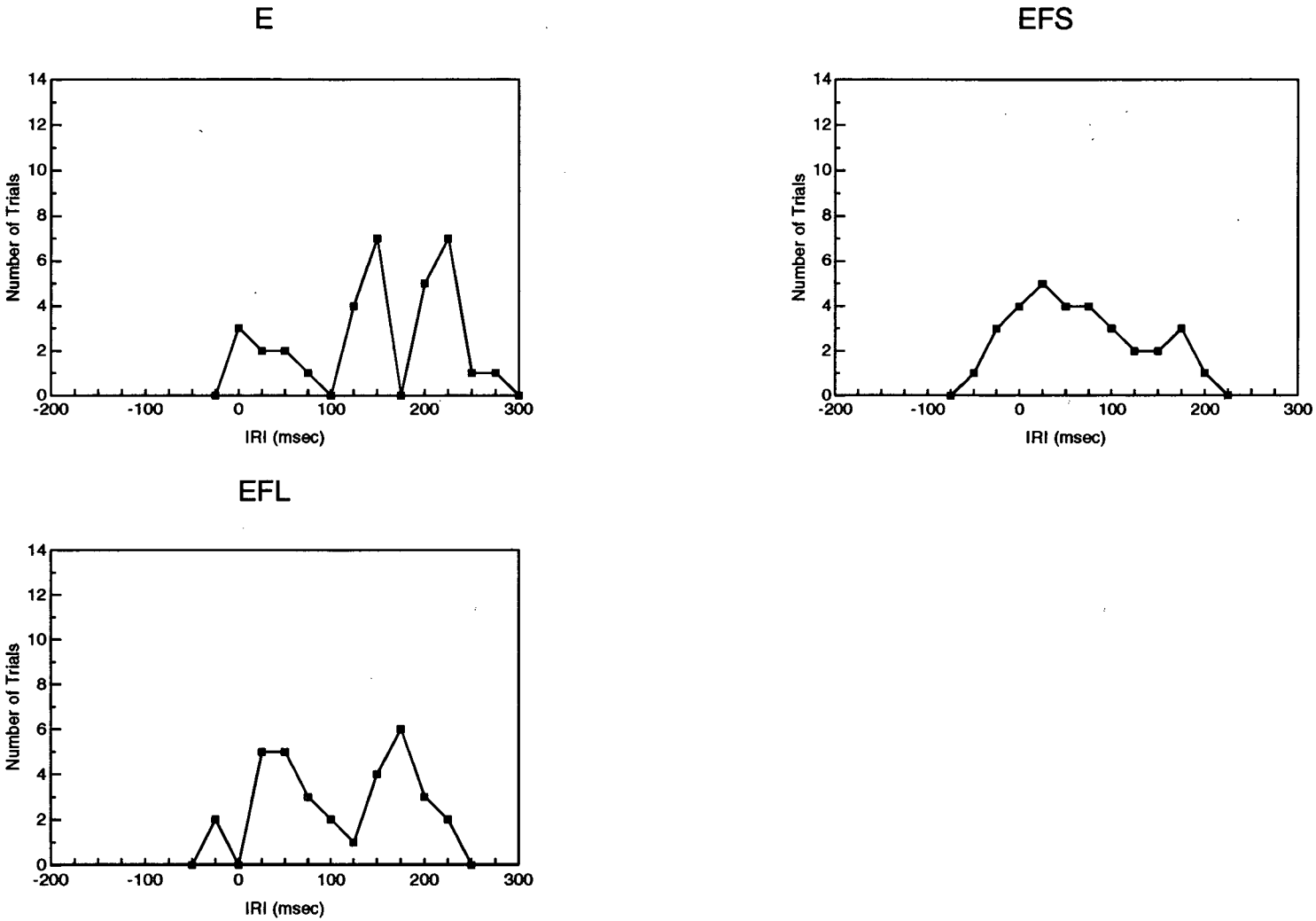


Figure 10a: The PRP Effect

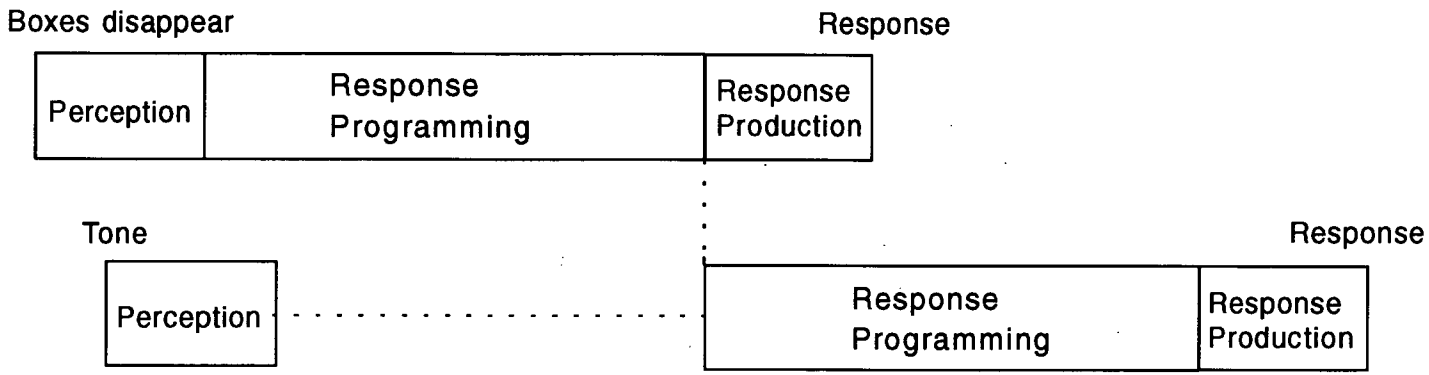
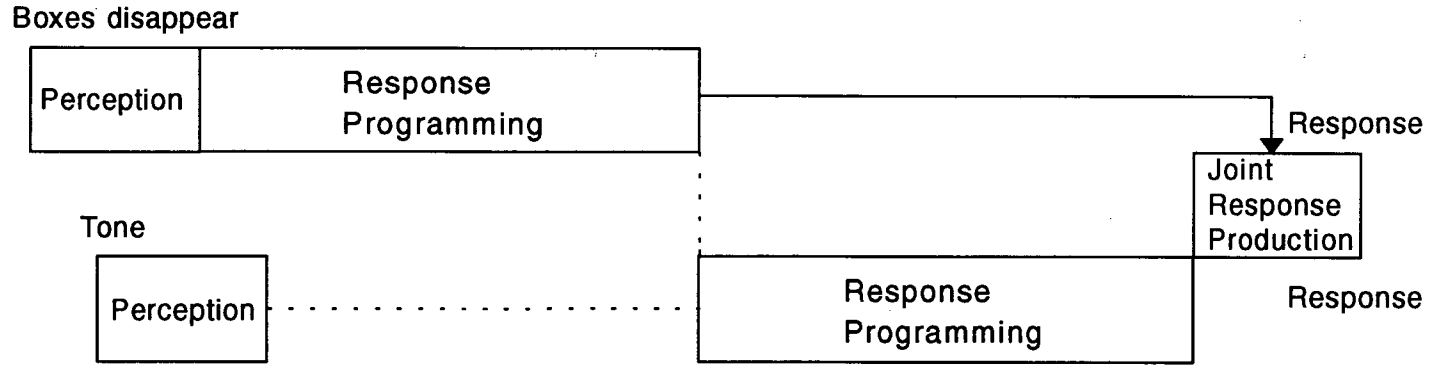


Figure 10b: The response grouping phenomenon



the EFS movement condition (see also Figure 11a), whereas for the EFL movement condition the Masseter response was initiated either 25-50 msec (see also Figure 11b) or 175 msec (see also Figure 11c) after the initiation of the Triceps response. Thus, it appears that when the secondary task stimulus occurred 100 msec after the onset of the primary task stimulus, the arm movement response was either initiated prior to the jaw clench response, as was shown in Figure 10a, or the arm movement and the jaw clench response were initiated in rapid succession. The latter phenomenon is referred to as 'conjoint responding' or 'response grouping' (e.g., Borger, 1963; Pashler, 1984; Pashler & Johnston, 1989). Figure 10b shows that the arm movement and jaw clench response can be produced in rapid succession, or as one conjoint response, when the execution of the arm movement response is delayed until the programming of the jaw clench response has been completed.

The second main finding of the present experiment was that the differences in MRT between E and EFL movements in the dual task condition were significantly larger when the probe occurred at the end of the extension movement (i.e., probe position 6) than when the probe occurred during the motor reaction time period and at the point of peak acceleration (i.e., probe positions 3 and 4). It is suggested that the Masseter response may have been delayed for the EFL movement in the dual task condition because the flexion movement was programmed at the end of the extension movement. Figure 12 shows a frequency distribution of the differences between the onset times of the Biceps (i.e., the prime mover for forearm flexion) and Masseter muscles at probe position 6 for all EFL trials. It is evident that the arm movement and the jaw clench response were initiated concurrently for the majority of the trials (see Figure 13 for the displacement profile and the three EMG profiles for one trial for which the probe occurred at the end of the extension movement in the EFL movement condition). Because the MRT was found to be lengthened at

Figure 11a: Typical data for an EFS movement with probe occurring at position 2

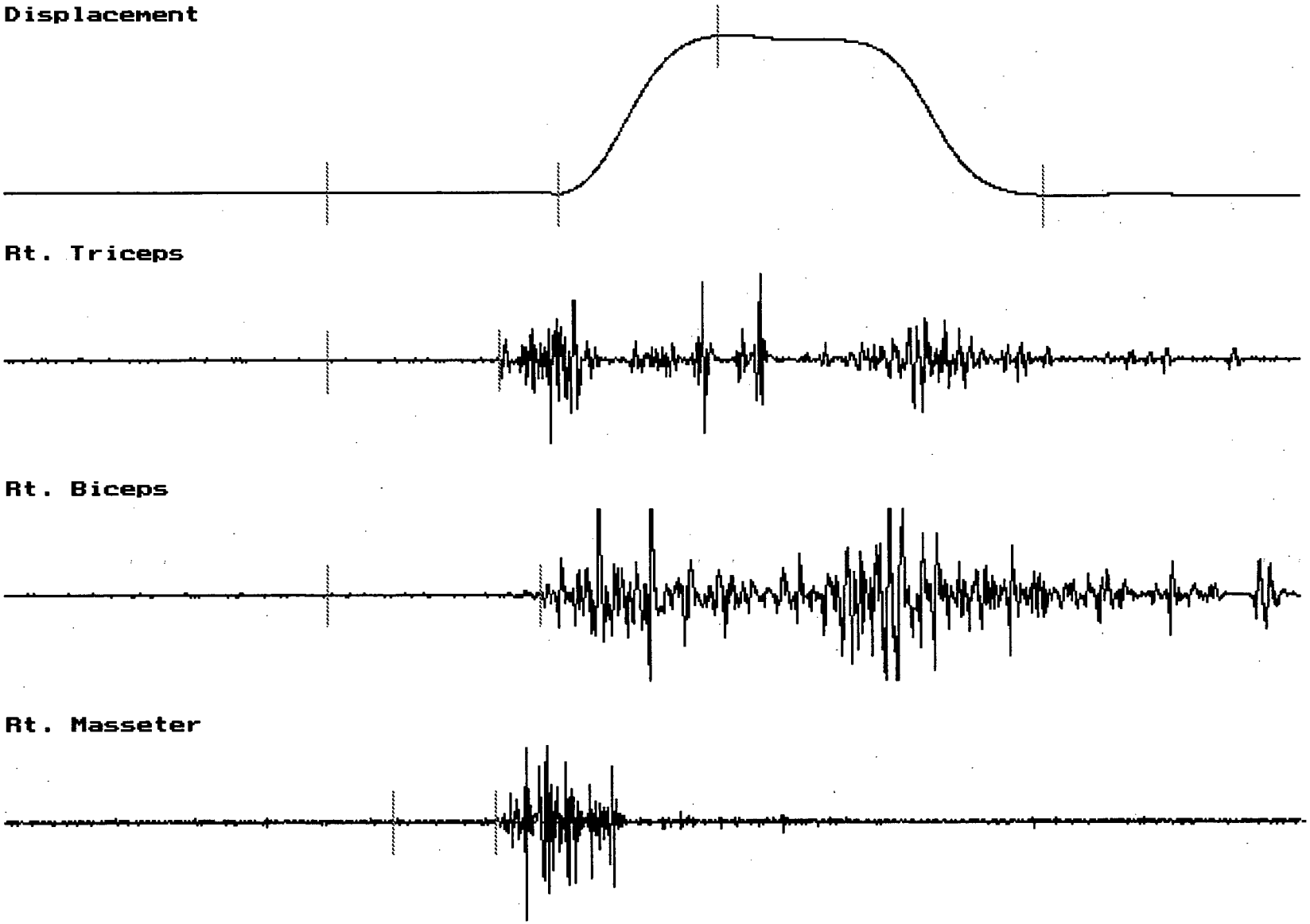
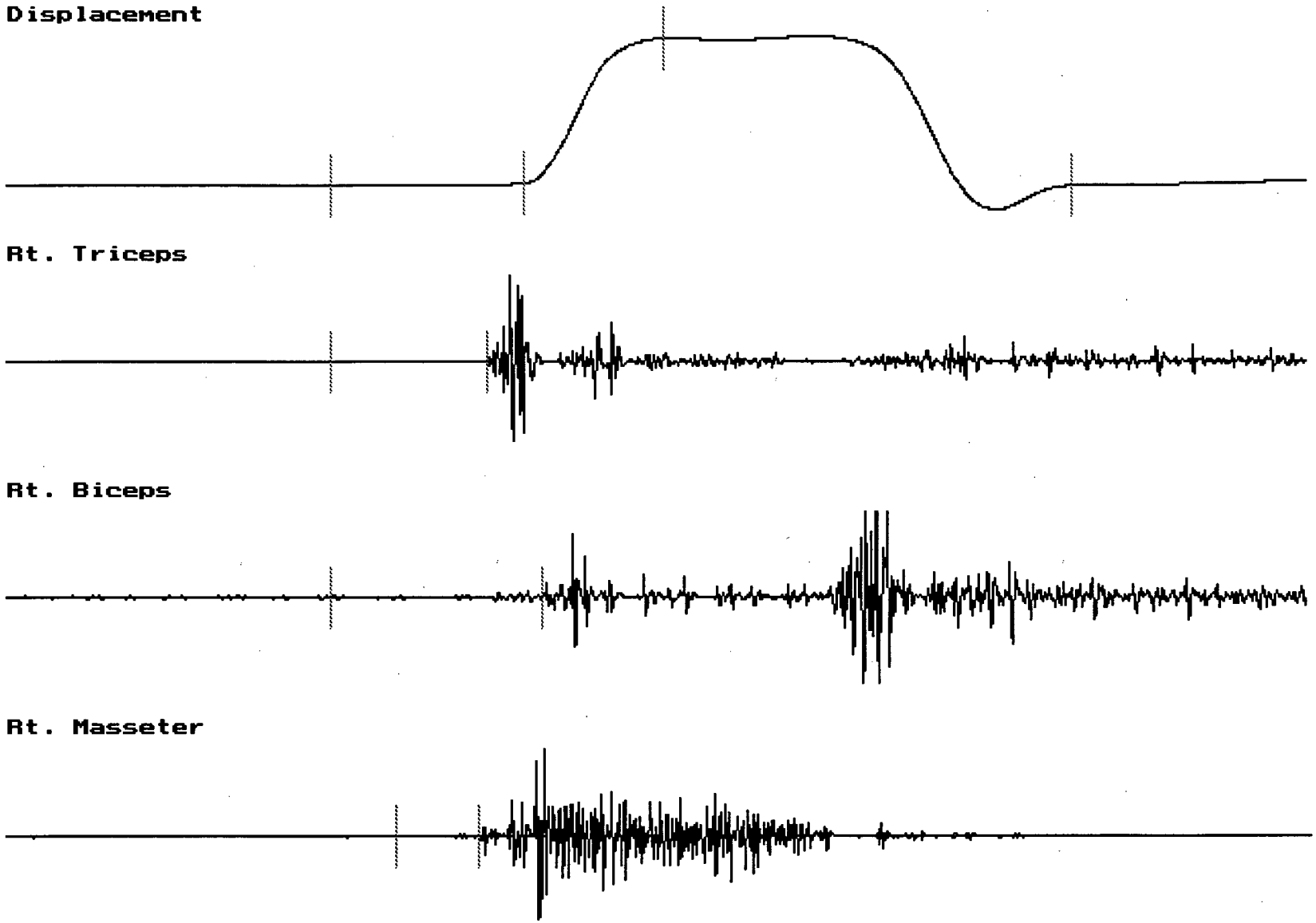


Figure 11b: Typical data for an EFL movement with probe occurring at position 2: Response Grouping



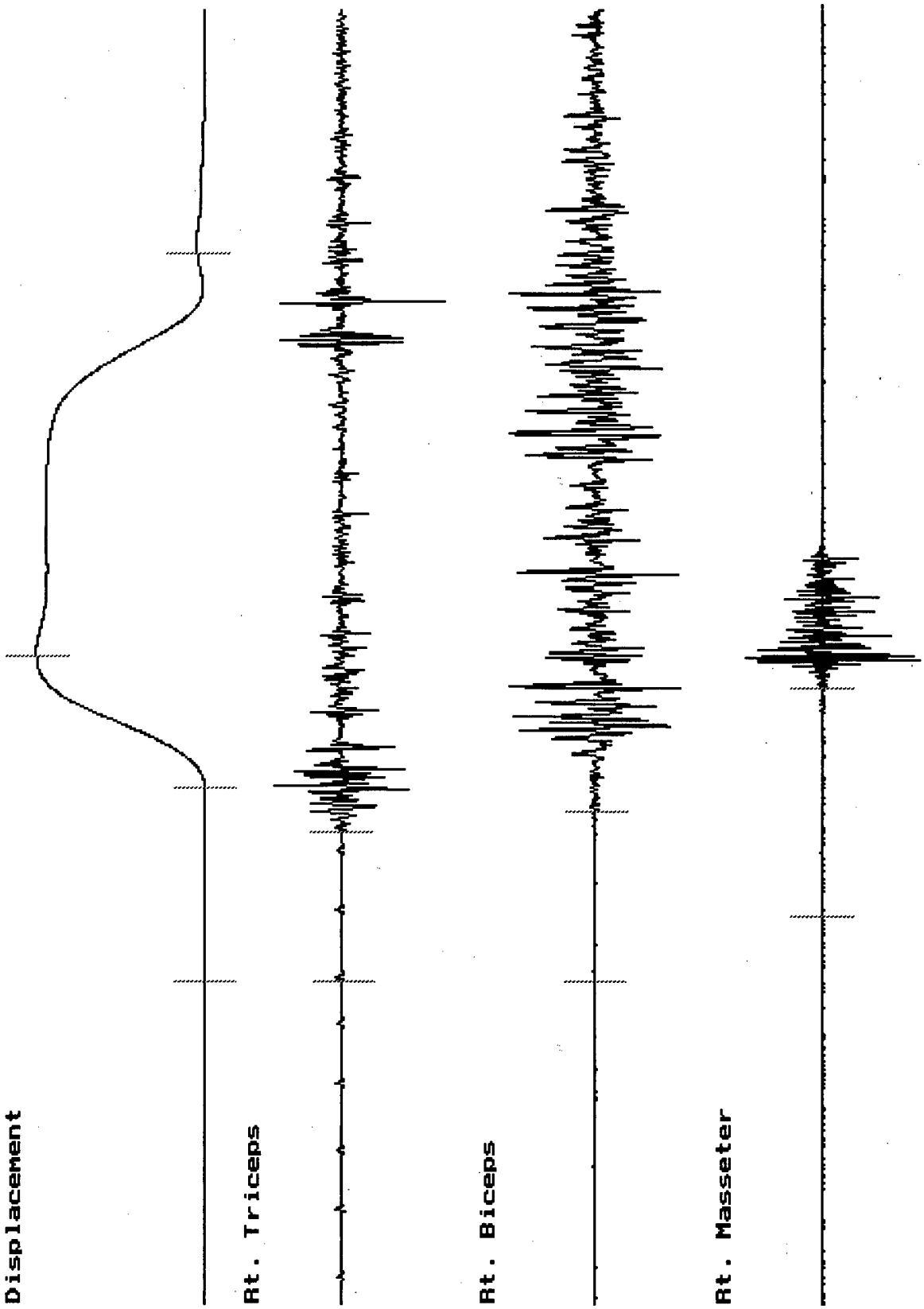


Figure 11c: Typical data for an EFL movement with probe occurring at position 2: The PRP Effect

Figure 12: Distribution of interresponse intervals for EFS and EFL movements at probe positions 5, 6 and 7

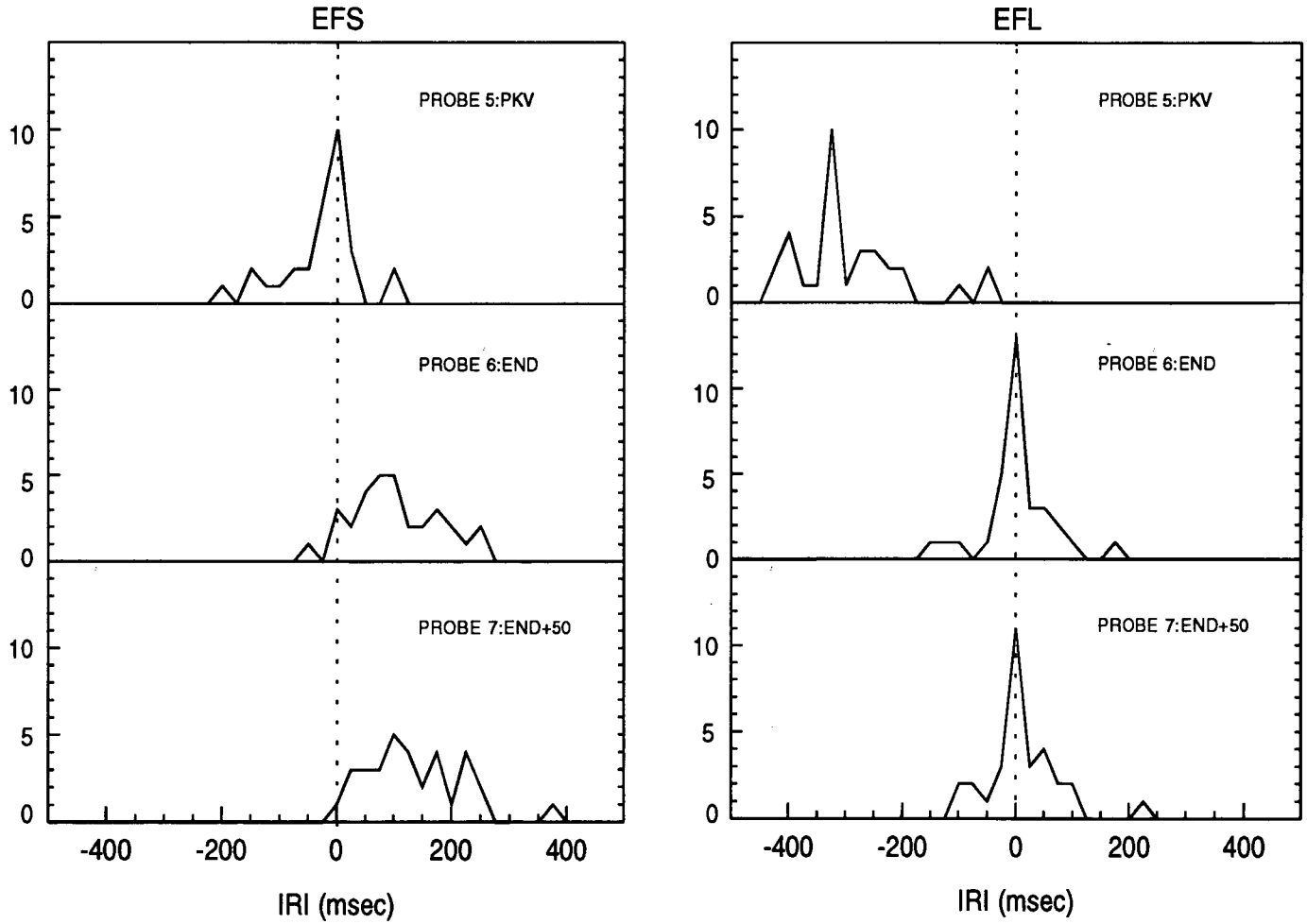
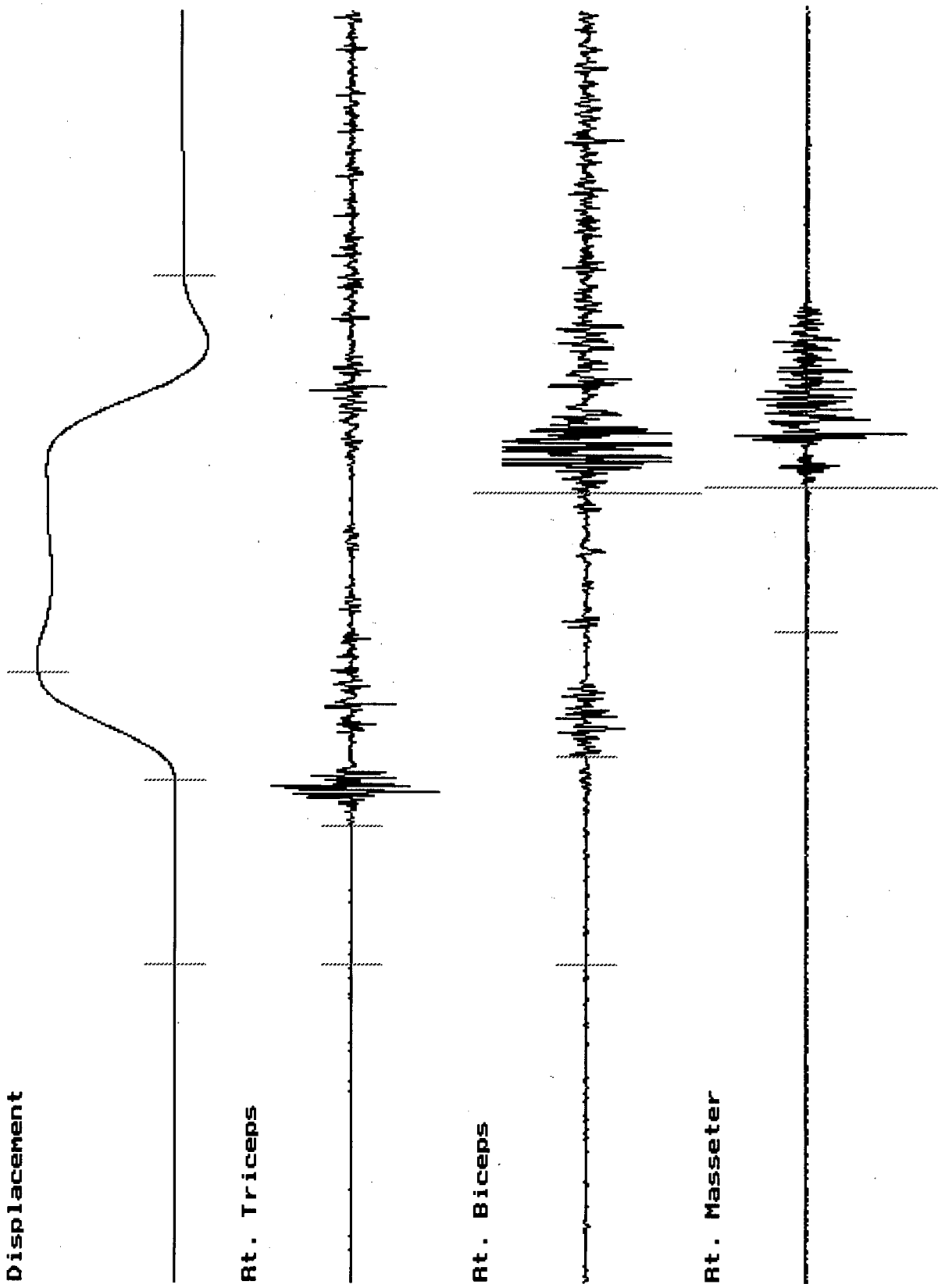


Figure 13: Typical data for an EFL movement with probe occurring at position 6



probe position 6 for the EFL movement, it appears that subjects may have delayed the execution of the jaw clench response until the programming of the arm movement response had been completed.

Figure 12 also shows a frequency distribution of the IRI's for all trials for which the probe occurred at positions 5 and 7 for EFL movements and at positions 5, 6 and 7 for EFS movements in the dual task condition. It is evident that the Biceps and Masseter muscles were also initiated concurrently for the majority of the trials at probe position 7 in the EFL movement condition and at probe position 5 in the EFS movement condition (see Figure 14a and b for the displacement profile and the three EMG profiles for one trial for which the probe occurred 50 msec after the end of the extension movement in the EFL movement condition, and at the point of peak velocity for the EFS movement). Subjects may have initiated both responses at the same time because the arm movement and jaw clench response may have interfered with one another when they were initiated close together in time. In order to avoid such interference, the two responses may have been produced as one conjoint response only after both responses had been programmed.

Figure 14a: Typical data for an EFL movement with probe occurring at position 7

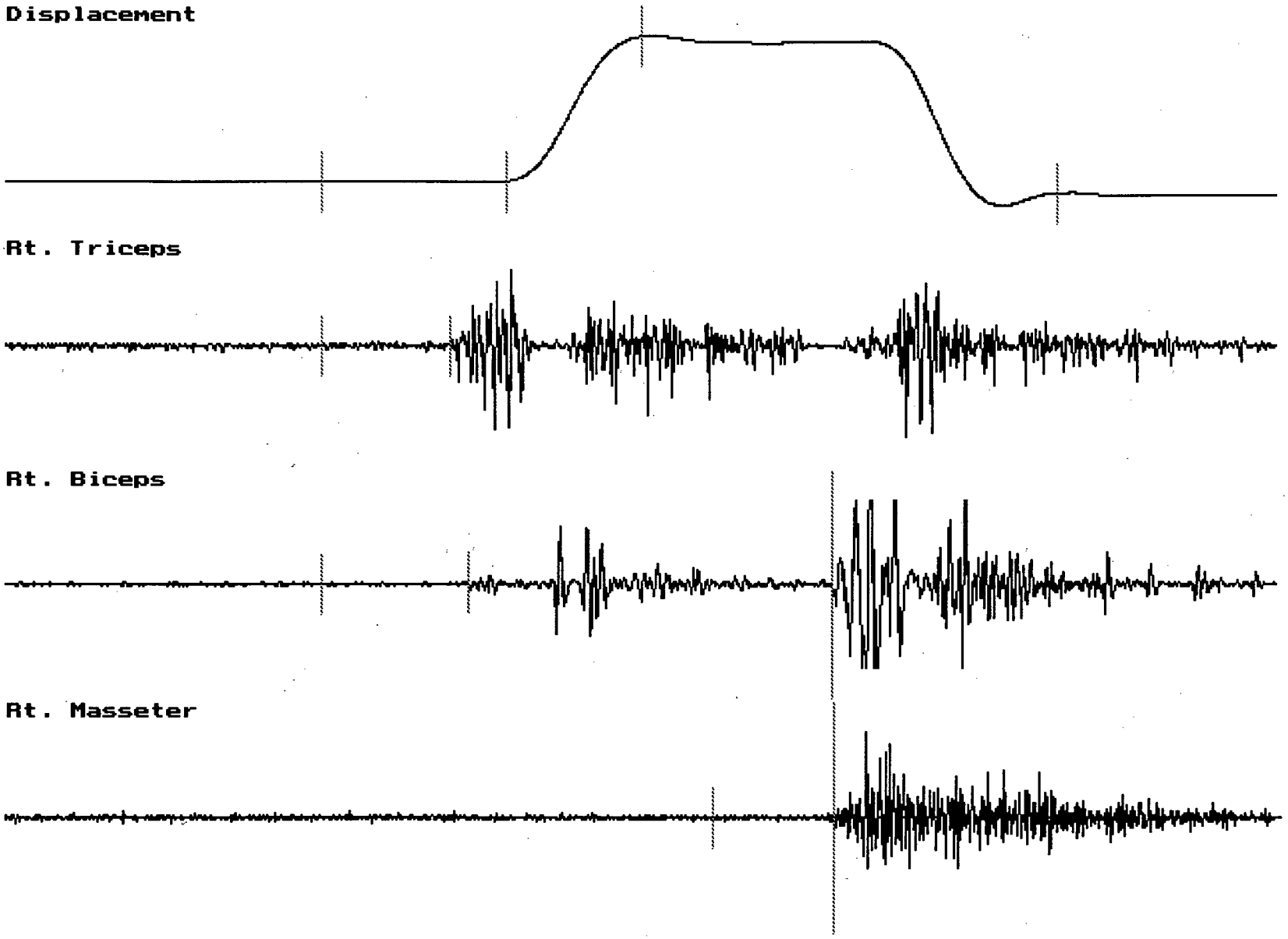
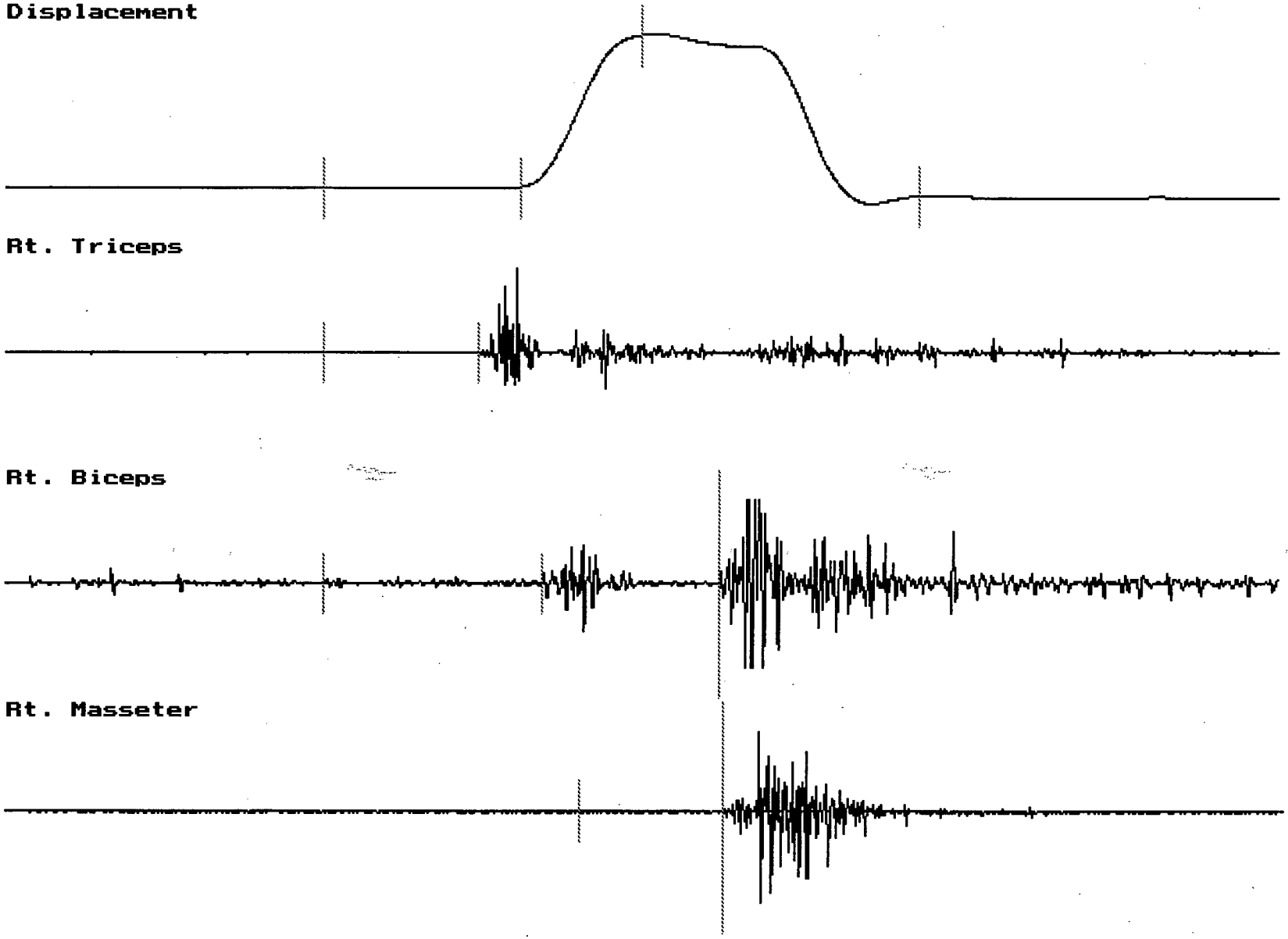


Figure 14b: Typical data for an EFS movement with probe occurring at position 5



GENERAL DISCUSSION

The main goal of the present experiment was to detect on-line programming as it occurred during the execution of forearm extension movements in an extension-flexion movement task. Evidence of on-line programming has been obtained in previous experiments through the use of several dependent variables, including probe reaction time measures (Glencross, 1980; Franks, Wilberg, & Fishburne, 1985), acceleration profiles (Van Donkelaar & Franks, 1991a, b), EMG recordings (Van Donkelaar & Franks, 1991a, b) and interval timing data (Ostry, 1980; 1983). In the present experiment probe reaction time measures were used to detect at which point during the execution of the extension movement on-line programming occurred.

It appeared that subjects were able to program the flexion movement of both EFS and EFL movements during the execution of the extension movement and/or during the pause time when the primary task was performed in the dual task condition. In using such a form of control, subjects were not required to program the entire extension-flexion movement prior to its initiation. As a result, the displacement and premotor reaction times of the extension-flexion movements did not increase above those of a forearm extension movement. By examining probe reaction time measures during the course of the forearm extension movement, a description could be given of where in time these on-line control processes took place. In the present study, the probe reaction times were lengthened for probes occurring at the end of the extension movement for EFL movements. This lengthening of the probe reaction time occurred because subjects appeared to delay the execution of the jaw clench response until the programming of the flexion movement had been completed. Subjects then adopted a strategy whereby they initiated the jaw clench and flexion response concurrently (i.e., response grouping, as evidenced by EMG activity of the Masseter and Biceps muscles). This 'response grouping'

strategy was also used when probes occurred during the pause time for EFL movements and at peak velocity for EFS movements.

In addition, the 'response grouping' strategy that was reported in the previous paragraph also appeared to be responsible for the delay of the execution of the arm movement response when the jaw clench stimulus occurred 100 msec after the arm movement stimulus. Subjects initiated both responses concurrently for the majority of the trials for EFS movements and for half of the trials for EFL movements (evidenced by EMG activity of the Triceps and Masseter muscles). However, the jaw clench response was delayed until after the execution of the arm movement response for the majority of the trials for E movements and for the other half of the trials for EFL movements.

It was suggested that subjects used the 'response grouping' strategy because the programming of the first response was in close temporal proximity to the programming of the second response. In order to avoid the interference that may occur when two responses are produced close together in time, subjects produced the two responses as one conjoint response only after both responses had been programmed. When the time interval between the two responses was larger, the response programming stages of both responses overlapped minimally, hence subjects appeared to complete the programming of the first response before they started the programming of the second response (i.e., the PRP effect).

In conclusion, by using probe reaction times measures, it was possible to detect at which point(s) during the execution of the extension movement on-line programming occurred. The findings of the present experiment indicated that subjects do indeed program EFS and EFL movements on-line. It appears that this on-line programming occurs at some point prior to the pause for EFS movements while it occurs at the end of the extension movement and during the pause time for EFL movements.

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APPENDIX A
MEAN VALUES AND STANDARD DEVIATIONS FOR ALL DEPENDENT VARIABLES

Table 6. Displacement reaction time for the single task condition

		Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E	x	232.7	225.6	235.1	238.7	235.9	234.8	229.5	233.2
	sd	41.5	35.8	39.6	47.6	36.4	37.4	45.3	36
EFS	x	253	252.5	250.2	260.5	254.3	263.6	244.3	254
	sd	38.9	50.4	42.9	37.7	48.4	51.1	45.7	39
EFL	x	249.6	250.3	258.1	251.2	259.6	258.1	250.5	253.9
	sd	51.3	39.1	39.4	33.7	47.2	52	55.9	39
		245.1	242.8	247.8	250.1	249.9	252.2	241.4	
		10.9	14.9	11.7	10.9	12.4	15.3	10.8	

Table 7. Displacement reaction time for the dual task condition

		Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E	x	341.8	248.8	271.7	284.1	270.8	265.3	269.4	278.8
	sd	49.1	27.8	34.3	29.2	37.7	28.3	25.1	29.7
EFS	x	333.2	285.5	289.1	302.8	298.4	289.9	292.4	298.7
	sd	59.4	52.8	51.4	49.7	58.7	52.2	48.4	16.3
EFL	x	342.6	270.6	283.6	283.4	285.9	279	279.3	289.2
	sd	52	28.3	38.1	29.7	46.5	35	48.8	24.1
		339.2	268.3	281.5	290.1	285	278.1	280.4	
		5.2	18.5	8.9	11	13.8	12.3	11.5	

Table 8. Premotor reaction time for the single task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E x	167.1	159.7	169.8	174.1	174	171.3	166	168.9
sd	45.7	34.5	38.3	45.1	35.2	35.4	46.8	36
EFS x	180.9	186.3	184.2	191.2	183.8	194.8	175.8	185.3
sd	36.8	49.9	36.1	36.4	47.1	50.9	42.7	37
EFL x	184.4	181.8	191.3	183.3	191.8	183.8	184.9	185.9
sd	48.5	37.3	40.2	33.3	44.3	49.2	57.9	38
	177.5	175.9	181.8	182.9	183.2	183.3	175.6	
	9.1	14.2	11	8.6	8.9	11.8	9.5	

Table 9. Premotor reaction time for the dual task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E x	274.7	184.7	204.3	215.5	205	198.8	201.1	212
sd	50.6	24.1	31.8	31.8	37.4	26.9	27.4	29.1
EFS x	264.8	215.2	216.5	231.9	230.2	221.8	222.2	228.9
sd	56.9	52.7	50.2	49.7	57.1	49.6	47.9	17
EFL x	274.8	199.5	213.5	214.6	218.2	209.1	210.7	220.1
sd	50.9	27.4	34.5	27	46.6	40.3	51.7	24.8
	271.4	199.8	211.4	220.7	217.8	209.9	211.3	
	5.7	15.2	6.4	9.7	12.6	11.5	10.6	

Table 10. Motor reaction time for the single task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E x	65.6	65.9	65.3	64.6	61.9	63.5	63.5	64.3
sd	10.2	7	8.9	7.7	10.3	9.8	11.4	7
EFS x	72.1	66.3	66	69.3	70.5	68.8	68.4	68.7
sd	11.2	9.5	10.8	8.4	10.6	10.6	10.7	8
EFL x	65.2	68.5	66.8	67.9	67.8	74.3	65.6	68
sd	7.5	9.6	9.1	10.5	14.1	11.3	7.2	7
	67.6	66.9	66	67.3	66.7	68.9	65.8	
	3.9	1.4	0.7	2.4	4.4	5.4	2.5	

Table 11. Motor reaction time for the dual task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E x	67.1	64.1	67.4	68.6	65.8	66.5	68.3	66.8
sd	7.7	7.5	7.8	8.9	8.4	7.8	7.3	1.5
EFS x	68.4	70.3	72.6	70.9	68.2	68.1	70.2	69.8
sd	6.8	8	8.1	9.2	7	8.7	5.8	1.7
EFL x	67.8	71.2	70	68.8	67.7	69.9	68.6	69.1
sd	7.7	8.4	8.5	8.8	7.7	9.6	10.2	1.3
	67.8	68.5	70	69.4	67.2	68.2	68.6	
	0.7	3.9	2.6	1.3	1.3	1.7	1.3	

Table 12. First movement time for the single task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E x	258.6	234	242.8	231.6	250.4	233.9	228.3	239.9
sd	64.4	60.3	65.3	53.4	74	67	53.8	51
EFS x	241.3	230.5	234.3	232.8	228.3	225.9	225.9	231.2
sd	62.5	44.3	64.4	62.7	61.3	53	47.4	50
EFL x	219.4	247	246	233.8	240.3	229.2	236.7	236.1
sd	42.9	64.8	40.2	56.9	59.3	55.8	59.3	46
	239.8	237.2	241	232.7	239.7	229.7	230.3	
	19.6	8.7	6	1.1	11.1	4	5.7	

Table 13. First movement time for the dual task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E x	249.6	236.8	230.7	233.1	235.7	229.8	227.1	234.7
sd	54.7	64.9	42.9	47.5	49.5	42.5	46.9	7.4
EFS x	232.6	221.9	226.6	221.4	219.8	230.3	226.9	225.7
sd	50.7	53.9	49.5	49.3	43.2	38.4	49.6	4.8
EFL x	233.7	222	228.9	235	237.1	223.9	229.1	230
sd	42.9	46.3	41.3	57	49.3	46.8	44.6	5.7
	238.6	226.9	228.7	229.8	230.9	228	227.7	
	9.5	8.6	2.1	7.4	9.6	3.6	1.2	

Table 14. First target accuracy for the single task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E x	0.18	-0.01	-0.14	-0.01	0.43	-0.85	-0.16	-0.08
sd	2.5	2.8	1.5	2.3	2.5	2.1	1.9	1
EFS x	-0.25	-0.20	1.22	-0.13	0.58	-0.31	0.37	0.18
sd	2.9	3	2.8	2.8	2.6	3.6	2.9	2
EFL x	-0.40	-0.09	1.85	-0.47	-0.55	-0.80	-0.77	-0.18
sd	4.3	2.5	2.6	2.4	2.9	2.5	3.5	2
	-0.16	-0.1	0.98	-0.20	0.15	-0.65	-0.19	
	0.3	0.1	1	0.2	0.6	0.3	0.6	

Table 15. First target accuracy for the dual task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E x	-1.07	0.70	0.41	0.12	0.69	0.72	0.46	0.29
sd	1.8	1.6	2.1	1.6	1.8	1.9	1.8	0.6
EFS x	-0.74	-1.09	-0.35	-0.41	-1.09	0.44	-1.27	-0.65
sd	2.6	2.6	3.1	2.8	2.1	3.3	2.2	0.6
EFL x	-0.65	-0.72	-0.12	-0.71	-0.17	-1.57	-1.22	-0.73
sd	2.4	2.8	2.5	3	2	3.2	2.2	0.5
	-0.82	-0.37	-0.02	-0.33	-0.19	-0.14	-0.68	
	0.2	0.9	0.4	0.4	0.9	1.2	1	

Table 16. Peak velocity for the single task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E x	331.6	343.7	337.1	359.3	335.2	353.5	351.2	344.5
sd	59.6	78.6	86.5	73.1	84.8	66.2	68.4	66
EFS x	328.2	347.9	347.3	345.0	356.4	341.9	354.1	345.8
sd	90.2	72.5	95.7	94.2	92.3	85.8	80.7	77
EFL x	359.7	326.2	350.9	333.6	335.5	338.8	333.3	339.7
sd	62.1	76.1	56.8	63.9	86.5	82.3	78.9	63
	339.8	339.3	345.1	346	342.4	344.7	346.2	
	17.3	11.5	7.2	12.9	12.2	7.7	11.3	

Table 17. Peak velocity for the dual task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E x	318.9	350.2	347.6	345.6	347.3	347.1	355.9	344.6
sd	74.3	82.9	71.3	63.8	75.7	78.9	73.6	11.9
EFS x	339.2	354	344	355.3	349.2	351.3	339.3	347.5
sd	89.2	74.6	70.2	67.3	71	70.7	74.6	6.7
EFL x	344.2	349.7	340.9	336.1	331.2	341.5	335.7	339.9
sd	80.7	87.4	67.2	74.8	89.2	85.1	79.1	6.1
	334.1	351.3	344.2	345.7	342.6	344.6	343.6	
	13.4	2.4	3.4	9.6	9.9	7.3	10.8	

Table 18. Time to peak velocity for the single task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E x	131.3	125.2	125.8	123.8	125.8	123.8	121.2	125.2
sd	25.8	23.2	20.2	22	24.4	22.7	19.2	20
EFS x	129.3	118.4	126.7	129.0	125.2	123.0	120.6	124.6
sd	25.7	19.5	29.1	26.4	24.3	24.6	22.6	22
EFL x	121.7	126.9	128.5	127.4	124.2	126.0	124.2	125.5
sd	18.8	18.3	19.4	22.4	20.5	24	20.2	17
	127.4	123.5	127	126.7	125.1	124.3	122	
	5.1	4.5	1.4	2.7	0.8	1.6	1.9	

Table 19. Time to peak velocity for the dual task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E x	130.8	124.5	119.6	119.7	125.1	122.9	120.5	123.3
sd	28.9	24	21.8	19.5	25.5	23.9	24.6	4
EFS x	122.7	115.3	119.8	117.8	118	118.9	117.7	118.6
sd	20.1	23.8	22.5	20.3	20.2	16.1	20	2.3
EFL x	120.7	119.2	125.6	122.3	122.3	124	125.9	122.9
sd	20.3	20.9	22.4	22.8	22.7	23.3	22.1	2.5
	124.7	119.7	121.7	119.9	120.9	121.9	121.4	
	5.3	4.6	3.4	2.3	2.9	2.7	4.2	

Table 20. Peak acceleration for the single task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E x	4491.1	4913.2	4791.5	5215.7	4908.0	5068.4	5090.3	4925.5
sd	1340.5	1592.4	1839	1736.8	1855.7	1495.8	1591.6	1459
EFS x	4638.9	5086.7	4927.3	4869.3	5015.6	4771.1	5125.3	4919.2
sd	1946.5	1557.1	2265.2	2144.2	2015.7	1858.7	1770.5	1734
EFL x	5090.9	4482.2	4790.4	4554.8	4886.6	4810.3	4811.3	4775.2
sd	1437.5	1694.7	1425.1	1526.2	2158.5	1613.2	1902	1483
	4740.3	4827.4	4836.4	4879.9	4936.7	4883.3	5009	
	312.5	311.3	78.7	330.6	69.1	161.5	172.1	

Table 21. Peak acceleration for the dual task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E x	4313.6	5114.6	4955.2	4874.7	4859.2	4925.2	5108.7	4878.9
sd	1763.8	1883.4	1740.9	1666.8	1870.9	1912.5	1983.8	269.7
EFS x	4724.4	5094.4	4878.5	5047.8	5034.5	4962.5	4822.1	4937.7
sd	1882.1	1813.4	1756.3	1722.3	1881.3	1718.2	1738.8	134.8
EFL x	4721.6	4950.3	4625.6	4675	4607.2	4865.2	4621.7	4723.8
sd	1959.3	2057.8	1621.9	1908.5	2116	2182.6	1918.6	133.8
	4586.5	5053.1	4819.8	4865.8	4833.6	4943.9	4850.8	
	236.4	89.6	172.5	186.6	214.8	26.4	244.8	

Table 22. Time to peak acceleration for the single task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E x	95.0	93.3	95.5	93.0	89.3	93.3	92.4	93.1
sd	11.6	15.9	17.6	17.6	17.5	22.1	18.2	15
EFS x	94.6	89.0	90.8	93.4	92.8	93.8	90.8	92.1
sd	22.5	15.1	23.4	22.6	20	24.1	16.6	18
EFL x	94.7	92.4	97.7	97.8	91.4	92.5	92.9	94.2
sd	16.7	16.4	17.1	23.4	18.2	13.4	19.1	14
	94.8	91.6	94.7	94.7	91.2	93.2	92	
	0.2	2.3	3.5	2.7	1.8	0.7	1.1	

Table 23. Time to peak acceleration for the dual task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E x	105.1	92.2	93.7	93.5	95.9	89.6	89.5	94.2
sd	24.4	20.6	21	17.9	23.1	19.3	20.1	5
EFS x	96.8	92.9	95.7	91.8	91.2	94.5	93.9	93.8
sd	16.7	23.2	23.2	17.9	17.9	18	18.2	2
EFL x	102	97.3	96.1	95.2	94.6	97.9	100.5	97.7
sd	19.5	20.1	18.7	20.2	23.8	23.5	23.6	2.7
	101.3	94.1	95.2	93.5	93.7	94	94.6	
	4.2	2.8	1.3	1.7	1.9	4.2	5.5	

Table 24. Total movement time for the single task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
EFS x	756.9	705.3	729.3	715.3	713.1	690.7	681.3	713.1
sd	160.8	110.2	118.4	101.1	113	98.5	103.6	97
EFL x	902.3	931.4	935.3	926.6	907.3	899.6	900.9	914.8
sd	64.1	137.1	141.9	86.7	96.1	162.8	127.5	93
	829.6	818.4	832.3	821	810.2	795.2	791.1	
	102.8	159.9	145.7	149.4	137.3	147.7	155.3	

Table 25. Total movement time for the dual task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
EFS x	727.9	745.4	710.9	725	716.1	751.3	752.8	732.8
sd	94.3	84.7	115.7	113.6	101.9	76.9	88.2	17.1
EFL x	897.4	924.4	956.2	957.6	994.3	926.1	941	942.4
sd	87.7	97	93.5	113	113.7	83.9	107.6	30.9
	812.7	834.9	833.6	841.3	855.2	838.7	846.9	
	119.9	126.6	173.5	164.5	196.7	123.6	133.1	

Table 26. Pause time for the single task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
EFS x	79.8	90.2	75.1	83.2	84.3	76.5	77.3	80.9
sd	26.2	27.5	31.4	27.2	25.7	32.2	29.4	14
EFL x	258.3	269.8	271.1	245.7	255.5	260.3	269.4	261.4
sd	42.7	46.8	32.8	43.7	34.9	68	68.2	26
	169.1	180	173.1	164.5	169.9	168.4	173.4	
	126.2	127	138.6	114.9	121.1	130	135.8	

Table 27. Pause time for the dual task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
EFS x	76.3	82.8	76.8	82.8	79.3	95.6	96.2	84.3
sd	28.3	14.1	19.7	21.4	23.3	17	23.9	8.4
EFL x	243.1	272.8	291.5	277.8	300.3	259.9	271.5	273.6
sd	22.2	26.2	38	36.5	62.1	26.9	24.9	19
	159.7	177.8	184.2	180.3	189.8	177.8	183.9	
	117.9	134.4	151.8	137.9	156.3	116.2	124	

Table 28. Masseter premotor reaction time for the single task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
CTR x	107.9	106.7	106.4	107.3	108.6	105.4	106.7	107
sd	11.7	15.5	12.4	14.9	13.2	15	9.2	1

Table 29. Masseter premotor reaction time for the dual task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	
E x	219.4	241.3	202.1	192.9	161.8	148.9	160.5	189.6
sd	69.7	65.8	35.5	36.3	32.7	32.8	41.6	34.2
EFS x	217.8	200	202	203.8	196.8	202.5	198.8	203.1
sd	47.7	67.6	51.3	57.9	67	59.8	43.9	6.9
EFL x	233.4	220.4	197.4	186.3	182	234.8	221.8	210.9
sd	54.6	76.8	36.5	55.9	66.7	57.6	51.7	22
	223.5	220.6	200.5	194.3	180.2	195.4	193.7	
	8.6	20.7	2.7	8.8	17.6	43.4	31	

APPENDIX B
OVERVIEW OF THE TOTAL NUMBER OF TRIALS REJECTED FOR EACH TASK CONDITION

This appendix gives an overview of the total number of trials that were rejected for the primary and the secondary task in the single and dual task condition (See Table 30, 31 and 32). It is evident that a large number of trials were rejected in the present experiment, especially in the dual task condition.

The following criteria were used for trial rejection when the primary task was performed in the single task condition. First of all, subjects were allowed five to ten practice trials and these trials were saved as 'bad' trials. Secondly, when performing the forearm movement task, subjects could either react too fast, or too slow to the visual stimulus and they could overshoot, or undershoot the target, both at the end of the extension movement and at the end of the flexion movement. Furthermore, they could fail to pause, or their pause time was too short, or too long for both EFS and EFL movements. For the secondary task in the single task condition, subjects could either react too fast, or too slow to the auditory stimulus. Subjects were also allowed five to ten practice trials in this task condition and these trials were again saved as 'bad' trials. In the dual task condition, subjects could make the errors that were described for both the primary and the secondary task in the single task condition. In addition, for some trials subjects did not react to the jaw clench stimulus when it occurred during the execution of the forearm movement. Also, when the jaw clench stimulus occurred 150 msec prior to the arm movement stimulus, subjects occasionally initiated the arm movement response upon presentation of the jaw clench stimulus. Furthermore, a number of trials were rejected because the jaw clench stimulus did not occur at its predetermined position. For the peak acceleration probe, we experienced problems with the computer algorithm that was used to detect peak acceleration. The probe that was designed to occur at the end or 50 msec after

the end of the extension movement sometimes did not occur because the acceleration trace did not cross the zero line at the end of the extension movement. Thus, subjects made more errors in the dual task condition than in the single task condition, because the dual task condition was more demanding in terms of experimenter imposed constraints.

Table 30. Number of trials rejected for the primary task in the single task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7
E	10	17	20	21	23	33	17
EFS	17	27	12	11	18	26	21
EFL	6	21	13	30	16	25	20

Table 31. Number of trials rejected for the secondary task in the single task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7
E	31	21	9	24	11	13	22

Table 32. Number of trials rejected in the dual task condition

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7
E	104	66	56	88	67	62	88
EFS	101	74	62	61	66	76	95
EFL	107	67	68	96	92	99	90

APPENDIX C

ON-LINE PROGRAMMING IN SIMPLE MOVEMENT SEQUENCES: A PILOT STUDY

INTRODUCTION

A commonly observed phenomenon in the production of movement sequences is that the time required to initiate a movement sequence (i.e., reaction time) increases with the number of response elements in the movement sequence. This phenomenon has been referred to as the response complexity effect (e.g., Christina, 1992). Henry and Rogers (1960) were among the first to show this relationship between reaction time and response complexity. Specifically, they demonstrated that a simple key lift response was initiated more quickly than a response composed of a key lift and additional movements to specified targets. More recently, this effect has been investigated using a variety of tasks, including typing (Sternberg, Monsell, Knoll, & Wright, 1978; Sternberg, Knoll, & Turock, 1990), pronouncing word sequences (Eriksen, Pollack, & Montague, 1970; Klapp, 1971; Sternberg, Knoll, Monsell, & Wright, 1988; Sternberg et al., 1990), writing words of different lengths (Hulstijn & Van Galen, 1983; Thomassen & Van Galen, 1992; Van Galen, 1991), making sequential hand postures (Harrington & Haaland, 1987) and executing sequences of gross arm movements (Fischman & Lim, 1991; Norrie, 1967; Ulrich, Giray, & Schäffer, 1990).

In general terms, models that account for the response complexity effect assume that the following processes take place prior to movement initiation. First, an abstract representation of the movement sequences (i.e., motor programs) is retrieved from long-term memory and, is then temporarily stored as subprograms in a short term motor buffer. Second, before execution of each individual movement in the sequence, the corresponding subprogram is

retrieved from the buffer, unpacked into its constituents and initiated. The model proposed by Klapp (1976, 1977) attributes the response complexity effect to the difference in time needed to read the motor program from long-term memory into a short-term motor program buffer. Alternatively, Rosenbaum and associates (Rosenbaum & Saltzman, 1984; Rosenbaum, Hindorff, & Munro, 1987) believe the response complexity effect is due to the time required to edit the program while it is in the buffer. Sternberg and colleagues (Sternberg et al., 1978) offer yet another explanation for this effect by attributing the increase in reaction time to the time needed to search the buffer for the subprogram that controls the first part of the movement response. Presumably, the search time increases with the number of subprograms in the buffer. Because these models assume that movement sequences are programmed prior to their initiation (from here on termed preprogramming), they predict a direct relationship between the number of response elements in a movement sequence (i.e., the number of subprograms of the motor program) and reaction time.

Recently, several studies have indicated that there are some conditions in which increases in response complexity do not lead to increases in reaction time. Specifically, researchers have shown that reaction time increased linearly in relation to the number of response elements when movements were completed as fast as possible, but either failed to do so, or did so non linearly when performed at a less than maximal speed (Canic, 1988; Garcia-Colera & Semjen, 1987, 1988; Van Donkelaar & Franks, 1991a, b). Rosenbaum, Hindorff and Munro (1986) have explained these findings by suggesting that in some instances, subjects do not program the entire movement sequence prior to its execution; rather, some aspect of this process carries on into the period of movement execution (from here on termed on-line programming).

Franks and colleagues (Franks & Nagelkerke, 1991; Franks, Ketelaars, &

Nagelkerke, 1992) found evidence of on-line programming in a series of experiments in which subjects performed forearm extension movements and two types of extension-flexion movements. For one group of extension-flexion movements, subjects were instructed to extend and flex in a continuous movement, resulting in an acceleration profile with only one zero line crossing (1 ZLC); For the second group, subjects were instructed to extend, pause for a short time and then flex, resulting in several zero line crossings of the acceleration profile (2+ ZLC). The main findings of the first experiment (Franks & Nagelkerke, 1991) were that the reaction times were significantly shorter for extension movements than for extension-flexion movements in the 1 ZLC condition. Thus, it was suggested that subjects were forced to preprogram extension-flexion movements that were continuous in nature. The reaction times for the extension movements were not significantly different from those of the extension-pause-flexion movements (2+ ZLC). On the basis of these findings it was suggested that subjects were able to program the flexion movement during the pause time (the mean pause time was 247 msec, the standard deviation was 56 msec). Franks, Ketelaars and Nagelkerke (1992) conducted a second experiment to determine if these reaction time differences were caused by premotor or motor reaction time increases. The movement conditions that were used in this experiment were identical to those of the first experiment. The results of this experiment indicated that the reaction times were significantly shorter for extension movements than for both types of extension-flexion movements. Contrary to the findings of the first experiment, reaction times for movements that contained only 1 ZLC in the acceleration profile were not significantly different from reaction times for movements that contained 2+ ZLC. Franks, Ketelaars and Nagelkerke (1992) suggested that the mean pause time for the extension-pause-flexion movement condition was too short to allow for on-line programming in this second experiment (The mean

pause time was only 100 msec, while the standard deviation was 50 msec).

The present experiment attempted to isolate the conditions under which subjects can program sequences of forearm movements on-line and those in which subjects are forced to preprogram. Because the duration of the pause time appears to have an impact on whether a movement sequence is preprogrammed or programmed on-line, this variable was manipulated in the present study. The movement sequences that were used in this experiment were forearm extension movements, continuous extension-flexion movements and two types of extension-flexion movements for which the time between successive extension and flexion movements was manipulated [i.e., subjects were instructed to make either a short pause (approximately 50 - 100 msec), or a long pause (approximately 200 msec)].

It was hypothesized that when movements are preprogrammed, the reaction time required to initiate those movements will increase as the response complexity is increased; When movements are prepared on-line, the reaction time will not increase with increases in response complexity.

METHOD

Subjects

Fourteen right-handed male and female university students, aged between 19 and 30 years, volunteered to serve as subjects in this study. All were naive as to the hypotheses under investigation and none had previous experience with the experimental task or procedures used. Subjects were paid $ 10 for volunteering to participate. The experiment was carried out according to the ethical guidelines laid down by the University of British Columbia behavioural sciences screening committee for research and other studies involving human subjects.

Task and Apparatus

Subjects were required to make arm extension and extension-flexion movements in the horizontal plane, through a range of 45 degrees (from 67.5 degrees to 112.5 degrees - where 180 degrees was defined as full extension). The right forearm was positioned on a manipulandum which consisted of a padded horizontal lever attached to a bearing-mounted vertical shaft, such that the elbow was coaxial with the axis of rotation. The right hand was supinated to grasp a vertical handle at the end of the lever and the position of the handle was adjusted to accommodate for varying forearm lengths. Subjects were secured in their seat with a shoulder harness in order to keep the contribution from the shoulder muscles constant within each movement condition and their arm was secured to the manipulandum with Velcro straps. In addition, the height at which the subjects were seated was adjusted so that the shoulder angle remained constant in the frontal plane across all subjects.

Subjects viewed an oscilloscope screen that was positioned directly in front of them at a distance of 50 cm. Two "target boxes" (consisting of four cursors spaced 1 centimeter apart) and a response cursor were displayed.

These target boxes were 10 cm apart at the horizontal center line of the oscilloscope screen: 5 cm to the right and left of center.

An optical encoder (Dynapar E20-2500-130), attached to the shaft of the manipulandum and custom made computer interface card allowed for high speed sampling of the angular position of the manipulandum (the sampling rate was 1000 Hz).

Angular acceleration data were obtained through the use of a Kistler accelerometer (type 8638B50, ± 50 G), positioned at the end of the manipulandum, 42 cm from the center of rotation. Its signal, which was measured in volts, was filtered with an active lowpass filter (Krone-Hite, # 3750) set at 50 Hz and then sampled.

Electrical activity from the medial head of the right Biceps muscle and the lateral head of the right Triceps muscle was monitored using Ag/AgCl surface electrodes (8 mm diameter). The electrical signal from the two sets of surface electrodes was amplified by a multichannel electromyographic (EMG) system (model 544, Therapeutics Unlimited Inc.) and raw amplified EMG signals (maximum ±10 V) were sampled at a frequency of 1000 Hz and stored for subsequent analysis.

All data were collected and saved on an MS-DOS 386-33MHz personal computer for later analysis. This computer was programmed (Borland Turbo Pascal 6.0) to control the entire experiment.

Independent Variable

One variable, the complexity of the movement response, was manipulated in this experiment. The subjects completed extension (E), extension-flexion continuous (EFC) and two types of extension-flexion movements for which the time between subsequent extension and flexion movements (i.e., pause time) was manipulated. For one group of extension-flexion movements the pause

time at reversal was between 50-100 msec (i.e., extension-flexion short pause (EFS)). For the second group, this time was 200 msec (i.e., extension-flexion long pause (EFL)). The pause time was calculated from the angular acceleration profiles and was defined as the time interval between the second zero line crossing of the acceleration profile (at the end of extension) and third zero line crossing (at the beginning of flexion).

Experimental Procedure and Design

The experiment was comprised of one session, lasting about 1 hour. At the beginning of the session, the experiment and task were described to the subjects and informed consent was obtained.

The EMG electrodes were attached to the skin, following standard EMG procedures (Basmajian, 1974; O'Connell & Gardner, 1963). First, the electrode placement area was shaved to remove hair from the electrode site; second, the site was rubbed with an abrasive pad to remove the dead surface layer of skin; and third, the site was cleaned with a solution of 91% isopropyl alcohol. Electrode gel was rubbed into the skin at each electrode site to diminish skin impedances. Each pair of electrodes was filled with electrode gel (Parker Laboratories, Inc., Signa Creme) and affixed to the surface of the skin by double sided adhesive tapes (Converters, Inc., # AET-250). The electrodes were aligned longitudinal to the direction of the muscle fibers and the wires were taped to the skin to prevent movement artifacts. A ground electrode was attached to the left wrist.

The subjects were first required to complete as many practice trials as needed to perform the movements accurately. The subjects then performed one block of five to ten acceptable trials for each of the four movement conditions (E, EFC, EFS, EFL). The order of presentation of each movement condition was counterbalanced across subjects to control for any order effects.

Each subject was randomly assigned to a predetermined order of movement conditions. In order to discourage subjects from anticipating the onset of the imperative stimulus and responding prematurely, 20 % of trials were catch trials.

The procedure for each trial was as follows. At the start of a trial the target boxes and response cursor were visible on the oscilloscope screen. Subjects positioned the manipulandum such that the response cursor was centered inside the left target box (designated as -22.5 degrees) and then reported "ready", indicating to the experimenter that the trial sequence should begin. Two seconds after the subjects had reported "ready", the target boxes were removed from the oscilloscope screen for 250 msec. The target boxes then reappeared, signaling the start of the trial. After a variable foreperiod (1500 - 2500 ms), the two target boxes and response cursor were removed from the oscilloscope screen. This served as the imperative stimulus. In the extension movement condition, subjects were then required to move the response cursor to the right target (designated as +22.5 degrees). This movement was therefore an extension of 45 degrees. In the extension-flexion movement conditions, subjects were required to perform an extension movement to the right target and then a flexion movement back to the start position.

Once the subjects had completed the required movement(s), the target boxes and response cursor reappeared on the oscilloscope screen for 500 ms, marking the end of the trial.

Immediately following each trial the kinematics of the subject's response and the stimulus were displayed on a colour graphics video monitor (Zenith "Flat Screen" ZCM1490) which was positioned directly underneath the oscilloscope. The first display consisted of the subject's displacement during the trial. Two sets of vertical lines on each side of the monitor screen represented the two target boxes and the subject's displacement data were

displayed with the X axis representing displacement and Y axis representing time. The second display consisted of the subject's acceleration profile, reaction time and first movement target error (signed constant error in degrees).

The subject's attention was directed to the first feedback display for accuracy and then the acceleration profile display for trial acceptability as per the required movements and reaction time. The subject was then told that any trials with an error score greater than ± 1.125 degrees, or a reaction time less than 100 msec (indicating anticipation) or greater than 500 msec (indicating a lack of attention) were discarded from further analysis. Additional trials were administered until the subject had performed between five and ten acceptable trials for each movement condition.

During a catch trial, the variable foreperiod was extended and the target boxes were not removed from the oscilloscope screen. After five seconds the experimenter reported the catch trial to the subjects and recorded any movement as error.

EMG Analysis

Among the many methods used in the current motor control research literature for defining the onset and offset times of EMG activity, visual inspection of the raw, or the raw rectified EMG is by far the most widely used (e.g., Anson, 1982, 1989; Carlton, Robertson, Carlton, & Newell, 1985; Christina & Rose, 1985; Fischman, 1984). A second method is to design computer programs that determine the onset time of muscle activation by calculating when the level of activity has reached a value determined by either the product of baseline activity and a constant, e.g., ± 25 micro volts (Sidaway, 1988), or by a certain percentage of the peak amplitude of activity observed for a particular experimental condition, e.g., 10 % of the peak amplitude of the subject's

averaged rectified EMG profile (Schmidt, Sherwood, & Walter, 1988).

Recently, Ketelaars, Franks, Sanderson and Nagelkerke (1993) compared the various methods for defining the onset and offset times of EMG activity. It was concluded that when computer algorithms were used, the calculated onset times were overestimated and the offset times underestimated compared to the results of visually inspecting the raw and rectified EMG signal. The method of visual inspection of the raw and rectified EMG, however, did not provide reliable inter- and intra observer results. In order to improve the method of visual inspection, the following procedure was used. The raw EMG signals were first full-wave rectified and then low pass filtered using a fourth-order zero-phase-shift Butterworth filter with a cut-off frequency set at 30 Hz. Following this procedure, the experimenter was presented with a raw, rectified EMG signal (inverted) and a raw, rectified and filtered EMG signal on the computer screen. The experimenter placed a cursor at the first indication of heightened EMG activity above the baseline for each raw, rectified and filtered EMG signal and compared the placement of the cursor to the raw, rectified profile. This method provided reliable inter- and intra observer results (The inter observer reliability coefficient was 0.87; The intra observer reliability coefficient was 0.89) and therefore this method was used to detect the onset times of muscle activation.

Dependent Variables

Angular displacement, angular acceleration and two EMG profiles (Biceps and Triceps muscle) were recorded for each trial. Angular displacement was used to determine displacement reaction time, first movement time (for the forearm extension), movement accuracy to the first target and total movement time.

Displacement reaction time was measured as the time from the imperative stimulus to the start of angular displacement about the elbow joint.

For the purposes of this study, the start of angular displacement was determined using a computer algorithm. First, displacement data for 200 ms before the imperative stimulus were analyzed and the mean and standard deviation calculated. Second, the data collected following the imperative stimulus were scanned forward until the point where the subjects had moved more than five degrees from the starting position. Data were then scanned backwards until the point where the displacement profile was within the bandwidth of one standard deviation (calculated from data prior to stimulus onset). The start of angular displacement was the next point (1 msec) forward in time from that point.

First movement time (for the forearm extension) was calculated as the time interval between the start of angular displacement and the largest positive value of the angular displacement (the range of the extension movement was from -22.5 degrees to +22.5 degrees). Also, the angular position (measured in degrees) of the largest positive value was used to determine the accuracy of the movement to the first target. The constant error was calculated for each target. Subjects over-shooting the target received their positional information as the positive difference between the target position and the response cursor, while under-shoots were reported as a negative difference.

Total movement time (for the forearm extension-flexion movements) was the time interval between the start of angular displacement and largest negative value of the angular displacement profile (the range of the flexion movement was from +22.5 degrees to -22.5 degrees).

Through the use of EMG recordings, the premotor and motor components of the reaction time period were determined. Premotor reaction time (PMT) was calculated by measuring the time interval between the onset of the imperative stimulus and the first sign of heightened electromyographic activity above baseline. The PMT is thought to represent the time needed to

centrally organize, translate and channel the appropriate commands to the musculature responsible for initiating the desired response. Motor reaction time (MOT) was calculated by measuring the time interval between the first sign of heightened EMG activity above baseline and the initiation of overt movement (as measured by displacement values of the optical encoder). The MOT is believed to reflect the duration of non programming events [e.g., electromechanical delay and development of sufficient torque to initiate movement (Anson, 1982)]. It has been argued that, since motor time does not reflect delays associated with central planning, it is important to separate this time out of the reaction time period. This more sensitive process allows for better discrimination between the latencies associated with muscular activity and actual limb displacement, thus, leading to a more detailed interpretation of any differences in programming time (Anson, 1989; Christina & Rose, 1985; Sidaway, 1988).

The angular acceleration profile was used to calculate peak acceleration, peak velocity, time to peak acceleration and time to peak velocity. Peak acceleration was defined as the absolute largest value of the acceleration profile. Time to peak acceleration was calculated as the time interval between the start of angular acceleration (calculated in the same way as the onset of angular displacement) and the point of peak acceleration. Peak velocity was defined as the point where the acceleration profile crossed the zero line for the first time. Time to peak velocity was calculated as the time interval between the start of angular acceleration and the point of peak velocity.

Data Analysis

The displacement, acceleration and EMG profiles of each trial were visually inspected by three independent observers. Following this procedure, detailed results for each trial were obtained through the use of an analysis profile

program. These results were then imported into LOTUS 123 (Volume 2.2) for the calculation of means and standard deviations for each individual subject. From these individual data, group means and standard deviations were computed for the four movement conditions. The data were analyzed using the statistical package SYSTAT5.0.

Statistical Analysis

A multivariate mixed model MANOVA was conducted on selected groupings of dependent variables that were theoretically related. All reaction times were grouped together (displacement, acceleration, premotor and motor reaction time); time to peak velocity, time to peak acceleration and time to complete the first extension movement (first movement time) were grouped; finally peak acceleration and peak velocity were also grouped. Individual univariate analyses were conducted on the dependent variables total movement time and first target accuracy. A univariate ANOVA followed by a Tukey's HSD post hoc analysis was used to detect differences between the movement conditions if the Wilk's Likelihood Ratio was significant. The alpha level for the entire experiment was set at .05 and the Huynh-Feldt Epsilon factor was used to adjust the degrees of freedom for violation of the sphericity assumption.

EMG Profiles

Because the kinematic features of a movement are largely determined by the net muscle activity of the muscles involved in that specific movement, the resultant EMG activity was calculated and correlated with the acceleration profiles that were produced by all subjects in the four movement conditions. First, the Triceps and Biceps EMG profiles were rectified, filtered and combined, giving an "acceleration-like" profile. Because the area under the Biceps and Triceps curves had to have an equivalent area in order to sum to

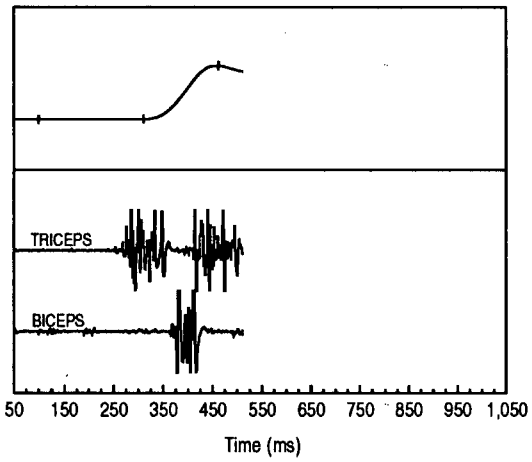
zero, much like the acceleration profile does at the end of the movement, the Biceps EMG profile was scaled before being combined with the Triceps EMG profile. Secondly, the combined EMG and acceleration profiles were compared using a cross correlation method to find the highest correlation and phase-shift values. The highest correlation between the combined EMG profile and the acceleration profile was found when the EMG profile was shifted 50 msec forward in time. This means that the EMG pattern occurred 50 msec before the resulting acceleration profile. This time frame is comparable to the MOT. These findings indicate that the EMG activity is reflective of the acceleration profile it produces. It is therefore legitimate to continue with a comparison of EMG patterns across movement conditions. Figure 15 depicts the muscle activation patterns that underlie the E, EFC, EFS and EFL movements.

The E Movement Condition

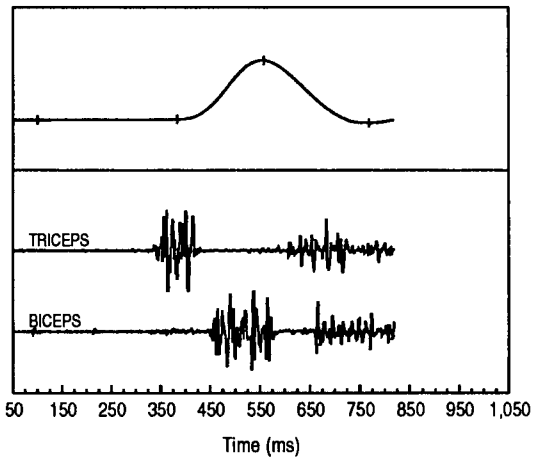
The muscle activation pattern of the extension movement can be described as follows: The initial activity of the Triceps muscle is followed by a silent period, coinciding with activity of the Biceps muscle and then by a second period of activity of the Triceps muscle. This triphasic activation pattern has been referred to in the research literature as the 'ABC - set' (Hallett, Shahani, & Young, 1975; Lestienne, 1979; Marsden, Obeso, & Rothwell, 1983), where 'A' is the action burst, 'B' is the braking burst and 'C' is the clamping burst. The action burst serves to accelerate the limb toward the target position; The braking burst is responsible for slowing down the limb and controlling its approach to the target position; and the clamping burst fixes the limb in the target position.

Figure 15 EMG profiles of the four Movement Conditions

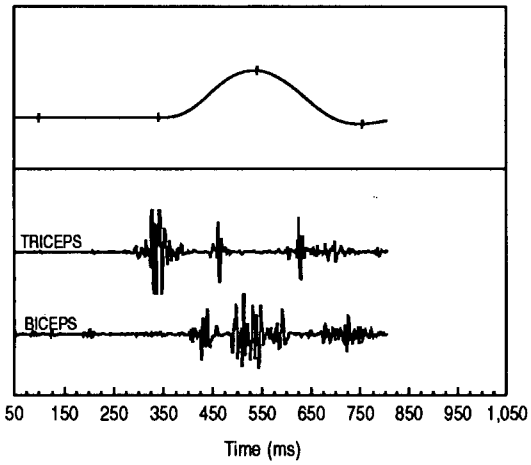
EMG Profile E



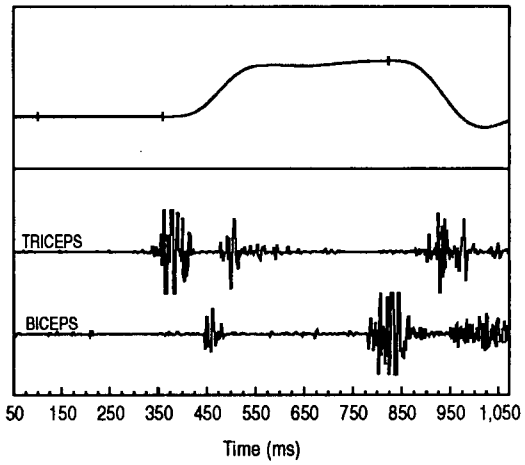
EMG Profile EFC



EMG Profile EFS



EMG Profile EFL



The EFL and EFS Movement Conditions

The muscle activation patterns of the extension phase of the EFL and EFS movements are identical to the muscle activation pattern of the E movement. The flexion phase of the EFL and EFS movements consists of initial activity of the Biceps muscle, followed by a silent period coinciding with activity of the Triceps muscle and then by a second period of activity of the Biceps muscle. For the EFS movement, the time intervals between the end of second burst of activity of the Triceps muscle and the beginning of the third burst of activity of the Triceps muscle and between the end of the first burst of activity of the Biceps muscle and the beginning of the second burst of activity of the Biceps muscle are notably shorter than those of the EFL movement.

The EFC Movement Condition

The muscle activation pattern of the EFC movement can be described as follows: During the extension phase, the Triceps muscle serves to accelerate the limb to the target. As can be seen in Figure 15, the Biceps activity must be initiated as the reversal is approached in order to brake the initial impulse from the Triceps (i.e., biphasic muscle activation pattern). After the Biceps activity has stopped the arm from extending, the Biceps muscle continues its activity in order to initiate the movement in the opposite direction. The Triceps activity near the end of the movement serves to brake the impulse from the Biceps and to stop the arm at the target.

RESULTS AND DISCUSSION

Subjects were instructed to pause for 50-100 msec in the EFS movement condition and the mean pause time was 58 msec (the standard deviation was 24 msec). In the EFL movement condition, subjects were instructed to pause for 200 msec and the mean pause time was 214 msec (the standard deviation was 91 msec). As expected therefore, the total movement time was greater overall in the EFL than in the EFS and EFC movement conditions (EFL = 658 msec, EFS = 493 msec, EFC = 447 msec).

The results of the MANOVA analyses indicated that Wilk's Likelihood Ratio was significant for all three groupings of variables (see Table 33). The displacement reaction time (DRT), acceleration reaction time (ART) and premotor reaction time (PMT) results mirrored one another and will therefore be presented together. Parallel findings for DRT and PMT were expected because in most experiments in which DRT was fractionated, high correlations were found between DRT and PMT (e.g., Christina & Rose, 1985; Fischman, 1984), although this is not always the case (Anson, 1982, 1989; Sidaway, 1988). In Figure 16, the group means for DRT, ART and PMT are presented for each of the four movement conditions. The results of a repeated measures (RM) ANOVA performed separately on the DRT, ART and PMT data indicated that the main effect of movement condition was significant for all three dependent measures (see Table 34). A post-hoc Tukey's test (Tukey, 1953) revealed that these latencies were significantly shorter for E than for EFC and EFS movements, while they were significantly faster for EFL than EFS movements.

Although the concept of response complexity may be used to explain the finding that the reaction times were shorter for E than for EFC movements, it was evident from the EMG and acceleration data (see Figure 15) that the EFC movement was not quantitatively varied along the same complexity dimension

Table 33. Summary of MANOVA's for dependent variables displacement reaction time (DRT), acceleration reaction time (ART), premotor reaction time (PMT), motor reaction time (MOT), time to peak velocity (TPV), time to peak acceleration (TPA), first movement time (FMT), peak velocity (PV) and peak acceleration (PA).

Effect	df	F	p (Huynh-Feldt)
Measure - DRT, ART, PMT, MOT			
Movement Condition	12,96	3.8	.0001
Measure - TPV, TPA, FMT			
Movement Condition	9,90	3.3	.0017
Measure - PV, PA			
Movement Condition	6,76	2.3	.0457

Figure 16 DRT, ART, PMT, and MOT vs. Movement Condition

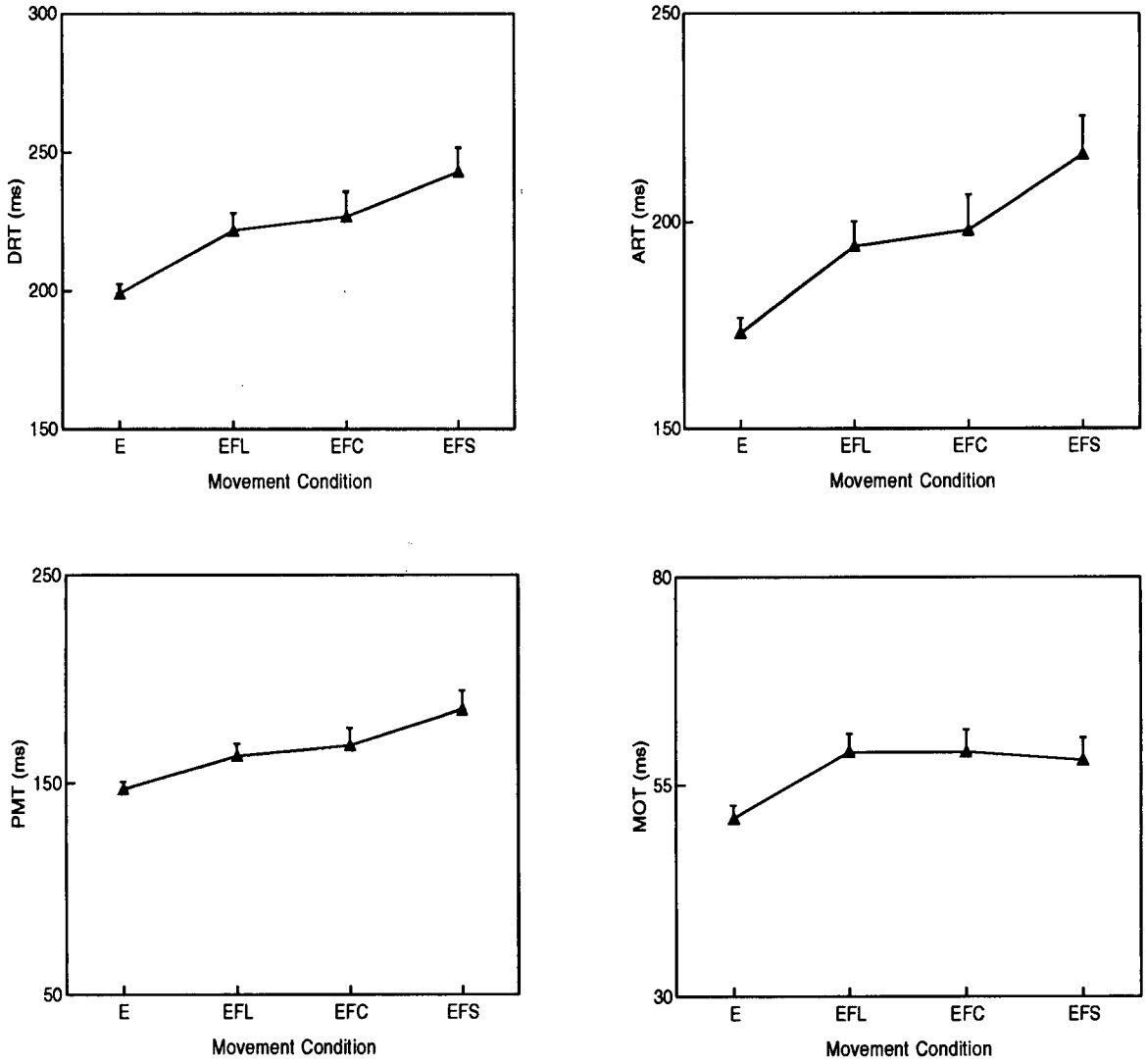


Table 34. Summary of ANOVA's for dependent variables displacement reaction time (DRT), acceleration reaction time (ART), premotor reaction time (PMT), motor reaction time (MOT), time to peak velocity (TPV), time to peak acceleration (TPA), first movement time (FMT), peak velocity (PV), peak acceleration (PA), total movement time (TMT) and first target accuracy (FTA).

Effect	df	F	p (Huynh-Feldt)
Measure - DRT Movement Condition	3,39	12.9	< .001
Measure - ART Movement Condition	3,39	11.8	< .001
Measure - PMT Movement Condition	3,39	9.7	.001
Measure - MOT Movement Condition	3,39	4.2	.012
Measure - TPV Movement Condition	3,39	1.4	.268
Measure - FMT Movement Condition	3,39	2.5	.077
Measure - TPA Movement Condition	3,39	0.6	.643
Measure - PV Movement Condition	3,39	3.9	.015
Measure - PA Movement Condition	3,39	2.6	.068
Measure - TMT Movement Condition	2,26	26.5	< .001
Measure - FTA Movement Condition	3,39	1.3	.276

as the EFS and EFL movements. That is, the movement was qualitatively different. If response complexity is to be defined on some quantitative dimension using variables other than behavioral ones (i.e., the number of response elements), it may not be valid to compare EFC with E, nor with EFS, or EFL. Although the displacement and premotor reaction times associated with the E movement were faster than those of the EFC movement, it does not logically follow that more time is required to prepare more response elements. It would be just as reasonable to assume that different responses require different preprogramming, hence different displacement and premotor reaction times.

The reaction time results also indicated that when subjects were instructed to pause for approximately 200 msec between successive extension and flexion movements (i.e., in the EFL movement condition), the displacement and premotor reaction times did not increase above those of a single extension movement. However, when this time was reduced to approximately 100 msec (i.e., in the EFS movement condition), the displacement and premotor reaction times increased significantly. These findings suggest that the minimum pause time required to program the flexion phase of the movement in this particular task falls between 100 and 200 ms; When the pause time is reduced to less than 100 msec, the entire extension-flexion movement appears to be preprogrammed.

The group means for motor reaction time are also presented in Figure 16. It was expected that the motor reaction times would be comparable for E, EFC, EFS and EFL movements, because the initial segment of each movement response was invariant [i.e., no significant main effects or interaction effects were found between movement conditions for the dependent variables first movement time, peak acceleration, time to peak acceleration, time to peak velocity and first target accuracy]. However, the results of a RM ANOVA

indicated that the main effect of movement condition was significant (see Table 34) and a subsequent Tukey test revealed that the MOT was shorter for E than for EFC, EFS and EFL movements.

Several other researchers have also reported increases in motor reaction time with increases in response complexity, but have failed to explain what caused this motor reaction time increase. Specifically, in an experiment in which subjects were required to tap a single target, or a series of circular targets as rapidly as possible with a hand-held stylus, Sidaway (1991) found that the mean motor reaction time for the one-tap condition was significantly shorter than the motor reaction time of the two- and three-tap conditions. Sidaway (1991) maintained that although the ANOVA indicated that there was a statistically significant main effect for the number of response elements, "the magnitudes of the motor reaction time differences between the conditions were very small" (p. 126), thereby implying that these motor reaction time differences were not meaningful differences in terms of human information processing. Similarly, Fischman (1984) found that when subjects had to contact from one to five targets, the motor reaction time for the one target condition was less than the motor reaction time for the three, four and five target conditions. Fischman (1984) stated that: "The difference in mean motor reaction time across all five target conditions was only 4 msec. Although statistically significant, this difference is far too small to account for the substantial simple reaction time effect; hence the simple reaction time effect is a central effect" (p. 415).

Van Donkelaar and Franks (1991a) have expressed some concern with regards to the usefulness of the motor reaction time measure. They indicated that the traditional view on motor reaction time, in which motor reaction time is believed to reflect the duration of non programming events [e.g., electromechanical delay and development of sufficient torque to initiate

movement (Anson, 1982)] is limited. Van Donkelaar and Franks (1991a) have argued that if it is assumed that movements can be programmed at any time before or during the execution of a movement sequence, then it appears plausible that this programming can also occur during the motor reaction time period. Similarly, if it is assumed that entire movement sequences are programmed prior to their initiation, then it seems faulty to assume that as soon as the muscles become active, this programming can no longer occur. Thus, when Van Donkelaar and Franks found an increase in motor reaction time with an increase in response complexity, they explained this by suggesting that some movement preparation may have occurred during the motor reaction time period. The results of the present experiment appear to substantiate their claim.

Even though Wilk's Likelihood Ratio was significant for the dependent variables time to peak velocity, time to peak acceleration and first movement time, the univariate ANOVA's for these three dependent variables failed to demonstrate a significant main effect of movement condition.

The univariate ANOVA for peak velocity (PV) demonstrated a significant main effect of movement condition. Also, a significant linear trend was evident for the PV values across the movement conditions ($F_{1,13} = 9.5$, $p = 0.009$). The PV value decreased from 468 degrees/sec for the E movement, to 436 degrees/sec for the EFC, to 428 degrees/sec for the EFL, to 417 degrees/sec for the EFS movement. The critical difference required by Tukey's HSD was 42.3 degrees/sec and only when the E movement was compared to the EFS movement, this critical difference was exceeded. No significant differences were found for the peak acceleration values across the four movement conditions.

It is suggested that the peak velocity values were lower for EFS movements because subjects may have programmed part of the flexion movement (or maybe the entire flexion movement) during the execution of the

extension movement. If this on-line programming did indeed occur, then some evidence of it should be present within the movement itself. Researchers have used several experimental manipulations to identify on-line programming as it occurs during the execution of a movement sequence. Van Donkelaar and Franks (1991a) performed a harmonic analysis on the acceleration profiles of arm extension/flexion movements that varied in speed to find evidence of on-line programming. They found that low frequency corrections occurred more frequently for the on-line programmed, slower movements. Figure 17 shows the results of a harmonic analysis that was performed on the acceleration profiles of the four movement conditions in the present experiment. It is evident that the EFS movement contains a larger number of low frequency corrections. This finding may suggest that some form of on-line programming is taking place during the execution of an EFS movement.

Van Donkelaar and Franks (1991a, b) have also looked to significant deviations within the acceleration profile for evidence of on-line programming. They found that significant deviations from a smooth curve occurred for on-line programmed, slower movements. Because the acceleration profile of the EFS movement does not show significant deviations, the suggested on-line programming explanation to account for the lower peak velocity values in the EFS movement condition does not hold.

Figure 17 Frequency Power Spectrum