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BIOCYBERNETICS: AN INTERACTIVE MAN-MACHINE INTERFACE

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REPORT SUMMARY

The research reported here and supported by the Advanced Research Projects Agency of the Department of Defense involves the detection of human bioelectric phenomena that have been made analogues of ongoing cognitive processes and the utilization of these phenomena to control and/or communicate with external devices. The technique is applicable to situations requiring rapid human intervention in the control of complex systems operation. The major advantage of this project is the virtually automatic control of systems by the trained subject.

We are training human subjects to respond to alpha-numeric symbols such that a discriminable response is obtained for each symbol. The symbols are a subset of the English alphabet. The bioelectric response is the electromiogram (EMG) recorded from the surface of the skin overlying muscle. The actual training is accomplished by utilizing the interactive computer programmed to present stimuli and deliver reinforcements of various kinds to the subjects, given the appropriate responses. The current technical report documents activities during the second year of support of the project. Presented below is a brief resume of the project's goals.

Upon mastery of generating appropriate EMG signals to isolated letters of the English alphabet, subjects will be required to correctly codify increasingly complex stimulus patterns. These stimulus patterns will take the form of simple words and eventually elementary phrases. This aspect of the project, the machine-to-man aspect, will emphasize the development of automatic responses to complex cognitive stimuli on the part of the subject. It is a necessary prelude to machine-to-man

communication. The latter will be accomplished by training to interpret machine generated codes presented through the EMG recording electrodes. These computer generated stimulations will be felt by the subject as tactile stimulations having the same patterning as the EMG response codes. It is anticipated that the combination of both approaches in a single trained subject will result in a rapid and precise two-way communication system between man and machine. There is evidence to believe that such a communication system will be capable of communicating in an interactive manner at a rate which is presently unattainable. Given the successful implementation of these goals, we will record and analyze brain potentials from the surface of scalp in an attempt to obtain even more "central" measure of cognitive functioning in EMG measures described above.

The immediate implications of this research are in: 1) the development of computer systems to decode and analyze communication. In this respect, we view this program as an alternative or adjunct to current efforts involving the development of a machine capable of decoding human voice; 2) monitoring the reactions and decision making processes occurring in stressful, complex, or pursuasive situations; 3) situations requiring rapid and continuous feedback information to the human controller; 4) situations where an interactive communication between man and machine are desirable but not currently practical because of time restraints or environmental restraints.

To date, we have been able to demonstrate the feasibility of training individuals to respond accurately and correctly to single alpha-numeric stimuli. We have also shown the feasibility of subjects spelling simple words using the EMG response apparatus. These words are then interpreted by the computer. We are currently testing a revised training protocol that should eliminate some of the problems discovered during intial spelling attempts. Given the successful solution of these problems we shall proceed to the machine-to-man communication aspect of the project utilizing computer generated tactile stimulations.

Introduction

The long-range objective of this project is the development of an efficient and accurate man-machine interactive method involving the use of biofeedback control. As such, it is our goal to utilize clearly structured bio-electrical aspects of human response generated in decision making. The major advantage of this approach is the virtually automatic interactive systems control by trained subjects.

We are training subjects to respond to alpha-numeric symbols such that descriminable response will be obtained to each symbol. The symbols are a subset of the English alphabet. The response is the electromiogram (EMG) recorded from the surface of the skin overlying muscle. The EMG is most directly an index of motor nerve activity rather than of muscle activity levels, since the magnitude of the electrical response is a direct function of the amount of neural activity imposed upon individual motor units of skeletal muscle. The EMG is always present upon sufficient neural activity to elicit muscle movement and is also detectable given neural activity insufficient to generate movement. Interestingly, when a subject is instructed to "think about" flexing a specific muscle, a recording of the EMG accompanying this cognitive process is possible. In short, the EMG has the unusual property of being activated by the mere thought of activating the response system, eg., the muscle (Leuba and Dunlap, 1951). This property of the EMG has been known for years (Hefferline and Perera, 1959) and has been utilized in several applied bio-engineering situations, most notably the control of prosthetic devices. In this case the subject, with sufficient training, becomes quite adept at controlling his prosthetic device and reaches the point where he need not actively conceptualize a muscle to produce the EMG signals necessary to control the limb and reach his goal. but merely "thinks" of the desired movement to be performed. The thought of the movement is sufficient to produce the necessary EMG's. Later in his training, he need not even think of the movement that is necessary to reach the goal, but merely thinks of the goal with the same lack of direct, conscious commands as does an intact human. It follows, of course, that the muscles used to control the limb cannot be occupied with other tasks that would produce error commands.

The project described herein deals with the capability of training a human subject to control and/or interact with complex electronic or mechanical systems. Basically the project involves the detection of bio-electrical phenomena that are analogues of ongoing cognitive processes and the utilization of these phenomena to control external events. The project also allows the system being controlled to communicate with the human operator in either a feedback or an interactive manner. In bypassing the subject's manual or verbal response appartus, an appreciable time saving is achieved. By eliminating the normal feedback/interactive modes of communication currently employed by machines (generally visual signals produced mechanically or electronically), a further potential time saving is realized.

The objectives during the first year of support were twofold:

1) To develop the interactive systems hardware and software, and
2) to train subjects to generate and respond correctly to alpha-numeric symbols using EMG responses.

The first annual progress report details these accomplishments.

Activities during the second year of support were directed toward the following tasks:

1) The elimination of errors as identified in the first year of support.

2) An analysis of the role of biofeedback in task acquisition.

3) Subject training on the sequencial response task.

4) An identification of sources of error from the initial sequencial response task. This led to redefinition of the training protocal both in terms of training strategy and in terms of EMG code assignments.

This report, the Second Annual Progress Report, details the above accomplishments.

Project Background

Subjects have been trained to generate sixteen different muscle patterns on cue. The process of training subjects to generate these precisely defined motor responses to visual stimuli initially proceeded from simple match-to-sample task to the codification of a subset of the English alphabet, utilizing these defined sets of responses. The responses currently being trained are the EMG responses from the skin surface overlying four muscles: left and right flexor pollicis brevis (thumbs), left and right abductor digiti minimi (little fingers).

Subjects are required to generate these EMG responses without appreciable movements of the muscles of fingers. This aspect of the task - generating the EMG's - has proved easy for the subjects. Subjects report that the task is a manageable one, and that it is not unduly stressful or difficult. Training takes place in conjunction with computer biofeedback. While we have employed both visual and auditory feedback in training to date (see below), we find that in this task immediate visual feedback is the most effective. Naive subjects are capable of learning the task in relatively short training period. On the basis of previous work, we have a strong impression that the manual capabilities of man utilized in terms of EMG activity rather than substantial movements far exceed expectations based on current manual task requirements.

General Procedures

This section contains in some detail the training procedures that we have employed in the project. We have seen fit to modify these procedures on the basis of work done, and later sections will document the changes. The criteria for selected muscles to be used in this project were based on the following. To obtain a satisfactory bio-electrical signal to noise ratio, the muscle had to be located on the superficial aspects of the body. The further restriction was that the muscles not lie under an overly thick layer of adapost tissue. Muscles were selected on the basis of their physical size, as a larger muscle will give a greater EMG response upon minimal neuromuscular activation. The task will eventually require very rapid patterns of EMG responses, thus the muscle selected had to be capable of responding at high rates of brief contractions. An initial design criterion was to limit ourselves to the utilization of surface EMG recordings. While much better signal to noise ratios and selectivity of recordings sites can be obtained with indwelling electrodes, it was felt that the practical constraints posed by this solution would rule out this procedure. Surface recording of EMG activity is capable of detecting responses from a number of muscles located adjacent one to another. Thus we were seeking a muscle which is relatively anatomically isolated. This anatomical isolation prevented cross-talk and interference from adjacent muscles which may or may not be activated during the course of training period. Muscles that were utilized in normal postural control were eliminated from consideration. For this reason we eliminated most of the large muscles of the limbs (they also are incapable of responding at high frequencies). Since we want to utilize a rather subliminal muscular contraction, muscles that have as high an innervation ratio as possible was selected. For practical reasons the EMG recording site had to be readily accessible for the placement of the surface electrodes without undue embarrassment or discomfort to the subject. After trial we eliminated the muscles of the face and head because they were either too small or were involved in largely involuntary movement associated with respiration, swallowing, eye blinking, etc. After extensive investigation the muscles deemed most suitable for this project were the muscles of the thumb and little finger on each hand. With these four muscles we have the capability of creating sixteen response combinations. Appendix A presents the EMG codes and the muscles associated with each of these codes.

For each subject the previously described muscles were mapped onto the surface of the overlying skin to determine the location yielding the best signal-to-noise ratio. Using differential amplification the most satisfactory results were obtained by placing the active electrode over the belly of the muscle and the indifferent over the distal tendon. All recording configurations employed earlobe grounding. Amplifier gain was from 30-150 V/CM. With a band pass of 1-75 Hz. The four channels EMG information were amplified and simultaneously written onto a pen-writing polygraph. The amplified EMG was fed to a series of voltage comparators which produce a standard logic level pulse from the voltage of the EMG exceeded a selective level. The PDP-12 computer's external sense lines then permitted decoding of the logic-level transforms of the EMG responses under software control.

Testing and training took place in a sound-attenuating ventilated chamber which was dimly lit (see Figure 1). The subjects sat in a comfortable stuffed chair and were not required to utilize any of their musculature to remain in a comfortable position. Subjects faced a window in the room through which they saw a panel containing various colored lamps which could be lit and a remote computer display upon which letters of the alphabet could be displayed (see Figure 2). A black cloth around these units reduced distracting visual stimuli to a minimum.

The Initial Training

In the early phases of project support, subjects were initially exposed to a four channel oscillographic display of EMG potentials. Recording electrodes were placed on the appropriate muscles, and the raw EMG was displayed on an oscilloscope placed in front of the subject. Subjects were allowed to generate EMG potentials of varying degrees of magnitude while watching the oscilloscope display. It was felt that the subjects could obtain an appreciation for the kinds of potentials that they could generate using their musculature. This initial pretraining lasted for several hours during which the subject was instructed to produce smaller and smaller EMG potentials. We have since determined that this initial pretraining is not necessary for the acquisition of the task at hand, and thus have abandoned its use.

<u>Patterned Light Training</u>

Each of the sixteen EMG combinations was assigned a particular alpha-numeric code as in appendix A. These codes can be considered as four lamps which can be lit or dark in various combinations. The lamp display panel, as shown in Figure 2, was employed for training subjects on the patterned light task. The lamp display panel consists of two rows of incondescent lamps. Lamps in the top row have orange lenses; lamps on the bottom row have green lenses. Single lamps on the extreme right and extreme left are colored red.

Rather than initially present the alpha-numeric display and the associated code as displayed on the lamp-display panel, we first trained the subjects to respond to the lamp display alone. It was felt that this was a somewhat simpler task and that the alpha-numeric display training would represent the second phase of the training.

The patterned light training task consisted of the presentation of a pattern of lit lamps on the upper row. The upper row of lamps, for convenience, are referred to as the S code (stimulus code) lamps. The subject was to turn on the lower row of lamps, such that the pattern of lit lamps in the two rows coincided. The lower row of lamps will be referred to as the R code (response code) lamps. Thus the task is a match-to-sample paradigm.

Every six to ten seconds the S code was displayed for 1.5 seconds. At the same time, the left hand red lamp was lit signalling the start of a trial (termed the go lamp). The subject then issued an appropriate EMG response. If successful in matching to the sample the right hand red light was lit (reinforcement lamp). At the end of the trial, the lamp display panel was turned off.

The S code presented on any trial was randomly determined by a high speed digital clock that transferred its count to the S code flip-flops upon command from a timer. The flip-flops in turn activated the lamp drivers in S code lamps of the display panel. The computer interpreted the S code and monitored the sense lines for the subject's R code. When a match was detected between the S code and R code, the computer signalled a reinforcement. This procedure provided a code-by-code analysis for each trial, consisting of an indication of the S code, the subject's response, and the latency for each muscle group in milliseconds.

The paradigm followed consisted of four consecutive daily sessions with 256 trials of patterned light training per day. Particular codes were presented in a random fashion. As a function of the detected R code, and at the experimenters option, the computer: 1) activated the

R code for patterned visual feedback, 2) activated audio oscillators, which were specially arranged around the subject for auditory feedback, or 3) displayed the R code alphabetic character on the alpha-numeric display unit as a form of cognitive feedback. Item number three was utilized in the following phase of training. These feedback options were evaluated for task acquisition effects and are presented below. A systems configuration to support the experimental control and data analysis of this phase of this experiment are presented in Figure 3.

Alpha-Numeric Training

Following sufficient mastery of the patterned light phase of training, subjects began work on alpha-numeric training procedures. Two different strategies were employed in affecting the transition from patterned light training to alpha-numeric training. The first procedure involved the simultaneous presentation of the S code lamps and the S code alpha-numeric display on the visual display unit. Through the repeated presentations of both patterned light and alpha-numeric displays, the subject learned the correspondence between the particular EMG codes and the alphabetic character. An alternative training strategy was to give the subjects a list of EMG response codes and the associated alpha-numeric characters. Subjects were instructed to learn the correspondence and were then placed into the testing situation, where they viewed only the alpha-numeric display. Comparable results were obtained with both strategies, and since the latter is considerably less time consuming, it was deemed advisable to employ this procedure rather than the former. The paradigm for alpha-numeric training was similar to that for patterned light training. Subjects received 256 trials of alpha-numeric display stimulation per day.

The data obtained from both the patterned light training and the alpha-numeric training were subjected to the following forms of analysis. Subjects were scored on overall percent correct performance per day to assess the progress being made during the training procedure. Overall latencies to respond as well as the time required for the successful generation of a code were computed. In addition, individual code analyses were made. These took the form of an error analysis, such that the relative propensity to produce an error for each code could be assessed. This general outline of the training procedures has been modified as will be shown in the following sections. The modifications were all made as a result of the experience with training subjects on the task at hand. In every case, changes in the training protocal were directed toward two ends; that of reducing errors, and speeding up the training process.

Biofeedback Study

The performance of subjects on the patterned light training and alpha-numeric training procedures, which has been documented in previous reports, has indicated that the production of codified EMG responses to alphabetic stimuli is feasible. In effect, to facilitate training of these responses, one of the probable factors affecting performance is the nature and amount of response related feedback given to the subject. To assess the nature of such task acquisition variables, we have exposed naive subjects to varying degrees of biofeedback in the paradigm as listed above. The year two semi-annual technical report contains a detailed analysis of the performance of most of the subjects in this biofeedback study. The results of this experiment will be summarized here and additional analyses will be presented.

There were two phases in the experiment. Phase I was match-to-sample paradigm employing patterned lamp stimuli. Phase II employed letter displays without the lamp display. Each phase consisted of four consecutive daily sessions of 256 trials each. Stimulus display time was 1.5 seconds. Intertrial interval was 6 to 10 seconds. Four groups were represented in Phase I. Eight subjects received total feedback which consisted of response contingent feedback in the form of the R code lamps, auditory feedback consisting of four speakers arrayed around the subject, and the reinforcement lamp which was lit upon a successful match to the S code stimulus display. The four speakers corresponded spatially to the four muscles of the hands under study. The speakers emitted a brief beep whenever the EMG was detected. Thus, the Total Feedback group received both patterned light and patterned sound feedback in addition to the reinforcement signal. In this condition, and in all others, the patterned light and sound feedback occurred irrespective to the correctness of the response. Only the reinforcement signal was contingent upon a correct response. A second group of eight subjects (Feedback) received feedback only in the form of the reinforcement signal. They were exposed only to the S code lamps and the reinforcement signal contingent upon response. Thus, the Feedback group receives information only about the correctness of a response, and no information regarding the nature of the responses per se.

Phase I had two partial feedback groups as well. The Light Feedback group (four subjects) were exposed to R code lamps and the reinforcement signal. The Tone Feedback group (three subjects) received the spatial auditory feedback and the reinforcement signal. Figure 4A shows the result of Phase I patterned lamp training over the four daily sessions for all four groups. The curves represent the mean performance of the subjects in terms of percent correct responses to all stimuli per session. All groups improved from session one to session four. The Total Feedback and Light Feedback groups were superior to the Feedback group and the Tone Feedback groups, although the latter improved by session four. An analysis of variance confirmed that there was a reliable sessions effect ($F=8.88$, $\underline{DF} = 3/76$, $\underline{P} < .01$) and an overall effect of treatments ($N = 9.84$, $\underline{DF} = 3/76$, $\underline{P} < .01$). Individual comparisons of all treatments across sessions (NEWMAN-KEULS test) indicated that all groups differed at the $\underline{P} < .01$ level of significance except for the comparison between Total Feedback and Light Feedback groups which did not reliably differ (see Table 1A). Similar comparisons between sessions across treatments indicated that all sessions differred $\underline{P} < .01$ level except for the comparison between days 3 and 4 (see Table 1B).

The ordering of the results of the four feedback groups suggest that the addition of the patterned auditory feedback did not facilitate acquisition of the task. Indeed, it appears as if performance may have deteriorated in Total Feedback as compared to the Light Feedback group due to the inclusion of the auditory feedback. The differences between the two groups are not reliable however. The performance of the Tone Feedback group is interesting in that the final level of performance approximates the superior groups after beginning at a lower level. Apparently patterned auditory feedback in this situation only minimally facilitates early performance, requiring many trials to show an effect.

Clearly the Feedback group is inferior to all others, indicating the value of specific biofeedback in this training situation.

Two of the groups (Total Feedback and Feedback) were exposed to additional training of Phase II of the experiment. In this phase the subjects were presented with randomly selected letters at 1.5 second display times in a 6-10 second intertrial interval. Given the response to the displayed letter stimulus, the Total Feedback saw the character generated (either correct or incorrect) displayed immediately below the stimulus display. Given the correct response, the reinforcement signal was presented. The Feedback group received only the reinforcement signal upon the generation of the correct response. There was no auditory feedback in phase II. The subjects were given a typed copy of the S codes and associated letters to learn between phases and were instructed to issue the correct EMG responses to the presented stimulus letters.

Figure 4B presents the average percent correct scores of the two groups as a function of session. Again, the Total Feedback group was superior to the Feedback group. An analysis of variance confirmed this observation of a treatment's effect ($F = 10.53$, $\underline{DF} = 1/86$, $\underline{P} < .01$) and indicated a reliable sessions effects ($F = 7.59$, $\underline{DF} = 3/86$, $\underline{P} < .01$). Interestingly there was no transfer of training effect evident in the scores of these subjects. This is perhaps not surprising, since although the responses are similar, the stimuli are markedly different. It is, of course, impossible to fully evaluate transfer effects, as a group receiving no previous training was not included in the design period.

A detailed examination of errors was done for Phase II of the biofeedback experiment. These data are fully presented in the semi-annual technical report for year two of this contract period. In summary, the stimulus letters resulting in the most response errors were m, p, and h. Each of these letters is characterized by a three-muscle non-symmetrical response. In addition, the letters m and h are similar in shape leading in potential misidentification. The stimulus letters d, r, s, and i were associated with the fewest response errors. These stimuli are characterized by symmetrical muscular responses (except for i, which is a single muscle response). By far the most common error, by a factor of 10, was the incorrect production of the code for the letter d. This code involves the activation of all four muscles. These error patterns can be explained in part by any gross movement on the part of the subject which would activate all the EMG channels. However, even in the absence of gross movement, subjects have a propensity for activating all muscles to these stimuli insufficiently well learned.

<u>Training Protocol Revision</u>

The biofeedback study just reported has provided us with a good deal of information regarding the training protocols which are an essential component of this project. The results of the biofeedback study indicate the value of the feedback and the acquisition of the task and point out the general value of specific feedback on motor/ conceptual tasks. We now seriously question the necessity for the patterned light training procedure employed heretofore. Although we cannot be certain of the value of such preliminary training, without experimental varification, it appears as if high levels of subject performance can be achieved rapidly without such pretraining. Current efforts employing naive subjects have eliminated the patterned light training as a precondition for embarking on alpha-numeric training. As will be documented below, the elimination of the patterned light training has had no dilatory effect on subjects' acquisition of the alpha-mumeric training.

Error analysis of individual code responses from the biofeedback study clearly indicate the necessity to restructure the EMG alpha-numeric code assignments. The revised EMG code system takes into account the relative frequency of various letters of the alphabet as they occur in normal usage. To this is coupled the "error quotient" of the subject's response to particular code assignments. These two factors, that of relative frequency and "error quotient", have been combined with the information content of the letters themselves into the structuring of a code as appears in Appendix B. The revised EMG code has been utilized in the training of several subjects thus far, and appears to offer the reduction of error signals to a lower level. The revised code is designed to represent the intersection of letter frequency, information content, and "error quotient".

Sequential Response Task

The sequential responding task is based upon the subject's ability to form rapidly and accurately the appropriate codes to the alpha-numeric stimuli previously discussed. The purpose is to give the subjects the opportunity to "spell" words using their EMG response apparatus. Simple words will be "spelled" either in response to alpha-numeric display (a match-to-sample task) or in an open-end response mode of interaction. In both cases the subject generated code will be displayed providing immediate visual reinforcement. In one case, visual/auditory cuing, the subject is required to match-to-sample, and is a form of machine-to-man communication. In the other case, subject initiated words, communication takes the form of man-to-machine. To date we have employed only the former procedure. The subject is exposed to a visual display of a three letter word of the English alphabet. His task is to sequentially generate the appropriate characters which will then appear on the display immediately under the stimulus code. Subjects were trained utilizing the EMG code as presented in appendix A.

A series of 128 three-character words were randomly presented to the subject. The strategy used initially in dealing with the detection of these sequential patterns was to define a "capture time window". This window was "opened" when the computer detected the first component (EMG signal) of any letter, and the window remained open for 256 msec. All components detected during the capture time window were defined as comprizing a character. The computer then waited until another response component was detected, and then opened the capture time window for the next character acquisition. This sequence of component detection and capture time window enabling was repeated three times (once for each character of the stimulus display). During each capture time period the decoded response character was displayed below the appropriate stimulus letter of stimulus word display.

The results of this task are presented in the following figures. Figure 5 shows the percent of correct spellings of 128 three character words over four days of training. The scores ranged from 65% correct on the first day of testing to 83% correct on the fourth day. A perhaps more instructive presentation of the performance over the four days is presented in Figure 6. Of the nine graphs shown, the top row three represent the percent of correct responses for a single component letter and for each relative position in the three-letter word. A single component letter is one that is produced by an EMG response from a single muscle. As can be seen, the performance in positions one and two exceed 93% correct for all four days. Performance for a single component response in the third position ranges between 85% and 91%.

The second row of Figure 6 shows performance by position over days for two component responses, one requiring the utilization of two EMG channels. Again, as with single component responses, performance in positions one and two was over 90% for all four days, with performance in position three falling off to a range between 70% and 88% correct. This pattern is repeated in the three component responses shown in the third row of the figure. Although the performance in this case is lower on the first day of testing, the scores improve by the fourth day to range from 95% correct in position one to 88% correct in position three.

Figure 7 depicts the fourth day performance by component number and letter position. This figure shows that performance regardless of the number of response components exceeds 95% for positions one and two, and is approximately 88% correct in position three. The reasons for the decrease in third position performance are ellaborated below, and were a basis for the evaluation of training procedures involved in the project.

Latency to Completion

Of particular interest in the question of sequential response tasks are the elapsed times observed in the completion of a particular letter as a function of the number of components involved. Figure 8 depicts the elapse time, or latency to letter completion as a function of number of components and position in word over the four days of testing. The top row of Figure 8 shows the latencies for the two components, and the bottom row shows latencies for three component codes. Since, by definition, single response component letters are completed when the first component is detected, the latency in these cases are zero. For the more complex forms of responding, a consistent decrease in completion latency is seen over the days of testing. A single exception the two component response in position three. In this case, latencies are shorter irrespective of day of training than are the latencies seen for two component codes in position one and two or three component codes in positions one, two and three. The two-component code latency in position three across days probably represents the lower limit of response completion latency possible. The response completion latencies on day four range from 30-50 milliseconds. This clustering of components is precisely what is required for a "capture window" timing strategy to function.

The result of this initial attempt at sequential character generation indicates that subjects can indeed "spell" words using their EMG response apparatus. However, the main value to us of this initial attempt was the identification of problem areas and sources of error in the generation of sequential responding. The following section will delineate these problem areas and our proposed solutions.

Error Identification and Rectification

The above sequential response task utilized the EMG code as listed in Appendix A. It is to be expected that subject performance would have improved somewhat given the utilization of the revised EMG code as presented in Appendix B. Aside from this, however, there are several problem areas which have been identified as interfering with sequential response task acquisition. It was noted that at times the subject made physical movements of the digits during the "spelling" of a word. These movements, however tiny, interfere with the capture timer feature of the sequential character task. An EMG response sufficient to generate movement is also a response that has a long time course period. If an EMG response is present on a particular muscle, after the time that the capture timer window closed, that movement would be detected as the start of a subsequent letter. Thus, an EMG response of sufficient magnitude and thus duration would most likely result in a error detected in the next capture time interval. An EMG response devoid of any overt movement does not have this characteristic, i.e. the response per se is terminated within 50 msec. Thus, our objective is to eliminate large EMG responses which are also associated with movements, and which falsely activate the capture timer. To alleviate this problem, we have implemented movement detectors, and are currently training subjects to perform with <u>only</u> EMG signals and no concomitant overt physical response. The movement detectors consist a sensitive piezoelectric crystals which produce error signals upon digit movement. The computer detects the error signals and provides the subject with this form of feedback.

It has proven impractical to require our trained subjects to eliminate large responses. We have thus employed the movement detectors on a new set of naive subjects. The strategy under which they are trained emphasizes the elimination of movements at the very onset of training.

The revised training protocal for these new subjects involves no patterned light training as a prelude to alpha-numeric task acquisition. Rather the subjects are begun immediately with visual alpha-numeric displays. Rather than require that the subject learn all sixteen codes simultaneously, we have trained them first on one component codes and then, given sufficient mastery of these codes, proceeded to two and three component codes. The emphasis on eliminating large EMG responses and thus error prone movements at the very onset, we believe, will eliminate the problem associated with the capture timer error signals.

Previous subjects have indicated to us that, given sufficient training, the EMG responses appear relatively "automatically". This automatic nature of the response is something that is very desirable for this project. To this end, we have taken steps to reinforce this aspect of responding. Subjects traditionally report that given sufficient overtraining, the probability of an automatic response increases. Thus subjects currently in training are receiving many trials with single, double, and triple component EMG codes. At the same time to ensure that the subject does not have sufficient time in which to issue commands on a non-automatic basis, we have reduced the S code display time. Currently response latencies across all letters average 220 milliseconds. Table 2 presents latency data for each letter and for each component in Phase II of the biofeedback study. While these latencies are very short in terms of normal human reaction time experiments, we feel that it is imperative to reduce them even further.

The ultimate speed of communication in a sequencial responding task depends to a large extent upon the feasibility of lowering the capture timer from its present 256 milliseconds to even shorter values. We feel this is feasible as the latency to generate a character as seen in the intial sequential responding task was from between 30 and 50 milliseconds. Figure 9 presents a latency histogram for two and three component characters. We feel that this low level performance does not reflect asymptotic responding in the task. We are particularly concerned in eliminating the long-latency responses (those exceeding 70 miliseconds) from the subjects response repetoire. This clustering of individual EMG responses for a particular character we term "bursting". It is our goal to establish burst response patterns that are as close to simultaneous as possible. If this is feasible, we can reduce the capture timer window even further.

In the reported sequential response task, the subject was presented with 128 different three letter words. In subsequent spelling tasks we will use a fewer number of different words and more repetitions of each word, enabling us to determine more accurately error patterns and probabilities. It follows, of course, that a well trained subject should be able to respond to a novel word with equal facility. In summary, the concept of using EMG's to spell words is a viable one. The task at hand is to maximize the accuracy of such a training protocal.

DISCUSSION

We have demonstrated the feasibility of training a human to generate reliably a cognitively linked response by using a heretofore non-utilized response apparatus. Our well-trained subjects report that they can often generate responses virtually automatically using this novel form of one way communication. When operating under short display times, they report that without "thinking of" making a response it nevertheless occurs. Subjects are intially quite surprized at this phenomena. Our goal is to develop a cognitive parallel to the operation of a prosthetic limb by an amputee. To this end, our further efforts in this direction will take the following forms. We will require our subjects to generate sequential alphabetic characters. They will be asked to "spell" words in response to a visual or auditory display, or to spell answers in response to questions. We propose that the virtually "automatic" firing of the EMG can be improved upon and extended from responded to a stimulus or query projected upon a screen to the thought of the stimulus symbol.

It is illuminating at this point to consider the rapidity with which our subjects are capable of responding to the alphabetic stimuli. As was shown in Table 2, the average latency for a trained subject was about 220 milliseconds. This value is seen to be as short as 130 msec by utilizing a warning signal prior to character display with well trained subjects. The latency measure represents the time elapsing between the presentation of the stimulus character and a successful generation is determined by the computer. In a carefully controlled animal experiment, Evarts (1966) obtained an average reaction time of 250 to 300 msec when a monkey was required to release a telegraph key to visual stimulation. The monkey was first required to depress the key, a function paralleling the use ofa warning signal. EMG signals from the extensor muscles of the trained monkey had an average latency of about 175-225 msec with a minimum latency of around 100 msec. It is remarkable that our subjects are capable of responding as quickly as they do, in that their's is not a simple reaction time task as was the monkey's. Our subjects must perceive the stimulus correctly and initiate appropriate motor patterns for each of the characters, thus one might expect a somewhat longer response time period. Humans involved in discrete stimuli reaction time tasks, generally have onset movement latencies of from 250 to 500 milliseconds, depending on the task (Fitts, 1964). It would thus appear that this system is capable of very short latency responses to stimuli requiring significantly higher levels of cognitive processing.

We have described in the sections above a proposed communications system. It is of interest to speculate as to the nature of the machine-to-man communication. Traditionally, communications from machines have been predominantly visual. It is conceivable that greater speed and/or reliability can be achieved by allowing a machine to communicate to a trained human by coded stimulation presented to his "response system." Using the present EMG electrodes located on the skin overlying muscle, we can pass non-painful current pulses through them coded in the standard fashion. With relatively little training, the subject may be able to interpret and respond to these machine-generated tactile stimulations.

The procedure of delivering stimuli to the limb or muscle involved in responding has been accomplished in both man and animal. Evarts (1973) trained a monkey to grasp a handle and to maintain a center position in the face of external displacing forces. He was able to record EMG activity in response to this stimulus as early as 24 msec after the handle was displaced. This is in contrast to 100 msec latency in a similar experiment employing a visual stimulus. In man the earliest EMG latency in an equivalent task was 50 msec. Both experiments indicate that this response, which is far faster than any other reaction time response, is not a reflex, i.e. it gradually developes with practice and has the properties of other learned phenomena. These data suggest that tactile coding by computer may prove to be a valuable tool in the development of a reliable man-to-machine interface.

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Appendix A

Below are the S Codes and their corresponding alphanumerics. The codes were devised with the following considerations in mind. First it was thought to be desirable to give the most commonly occurring alphabetic characters the simplest code. Thus, the letter E received a simple code: the right brevis alone. Since we have 15 codes to issue we determined the 15 most frequent letters and tested them for intelligibility. The 15 letters below comprise a high percentage of those letters actually used in normal communication and can convey a good deal of information.

The codes are given octal representation merely as a convenience.

Alphabetic Character	Left Minimi 4	Left Brevis 3	Right Brevis 2	Right Minimi 1	Binary Code	Octal Code
E			X		0010	02
A		X			0100	04
I				X	0001	01
N	X				1000	10
O		X	X		0110	06
R	X	X			1100	14
S			X	X	0011	03
T	X			X	1001	11
L		X		X	0101	05
C	X		X		1010	12
U		X	X	X	0111	07
P	X		X	X	1011	13
M	X	X		X	1101	15
H	X	X	X		1110	16
D	X	X	X	X	1111	17

The Xs indicate which of the lamps are to be lit for a given alphabetic character.

APPENDIX A-1

BINARY CODE TO EMG

Binary Code = 0 0 0 0

LEFT	LEFT	RIGHT	RIGHT
Obductor	Flexor	Flexor	Obductor
Digiti	Pollicus	Pollicus	Digiti
Minimi	Brevis	Brevis	Minimi
(Little Finger)	(Thumb)	(Thumb)	(Little Finger)

APPENDIX B

REVISED EMG S CODES

Alphabetic Character	Left Minimi	Left Brevis	Right Minimi	Right Brevis	Binary Code
E				X	0001
A		X			0100
I	X	X			1100
N	X				1000
O	X			X	1001
R		X		X	0101
S			X		0010
T	X		X		1010
H			X	X	0011
L		X	X		0110
C		X	X	X	0111
U	X	X		X	1101
M	X	X	X		1110
D	X		X	X	1011
Space/error	X	X	X	X	1111

The letter P is dropped in the revised code.

TABLE 1

A. Individual differences among treatments
(Newman-Keuls test)

	Total Feedback	Light Feedback	Tone Feedback	Feedback
Total Feedback		3	8.05*	17.37*
Light Feedback			11.05*	20.4*
Tone Feedback				9.35*

B. Individual differences among sessions
(Newman-Keuls test)

	Session 1	2	3	4
1 -		6.18*	15.4*	19.08*
2 -			9.22*	12.9*
3 -				3.68

* significant at $p < 01$

TABLE 2

POOLED OVERALL LATENCIES

	Left Minimi	Left Brevis	Right Brevis	Right Minimi	Average
A		235.			235.
C	220.8		228.9		224.9
D	201.	198.2	197.8	210.4	201.9
E			214.		214.
H	220.4	235.7	231.4		229.2
I				213.8	213.8
L		205.4		226.8	216.1
M	224.5	241.0		258.7	241.4
N	224.6				224.6
O		220.2	227.5		223.9
P	207.7		222.6	205.75	212.
R	226.7	212.9			219.8
S			213.5	232.	222.8
T	198.3			207.2	202.8
U		218.3	222.1	225.2	221.9
Average all letters	218.4	220.8	219.7	222.5	220.4

# of muscles	overall latency
1	221.9
2	218.4
3	226.1
4	201.9

FIGURE LEGENDS

Fig. 1 Physical arrangement of the training facilities

Fig. 2 Representation of the interactive display devices. The subject is seated one meter in front of the window.

Fig. 3 Systems configuration to support the experimental control and data analysis of the project.

Fig. 4 Biofeedback results. (A) Patterned light training over the four daily sessions for all four feedback conditions. (B) Letter training for two feedback conditions over days of training. Plotted are the group mean percent correct scores per day.

Fig. 5 Sequential response task performance. Percent correct spellings of 128 three character words as a function of training day.

Fig. 6 Percent correct spelling of one, two and three component letters for each training day as a function of position in word.

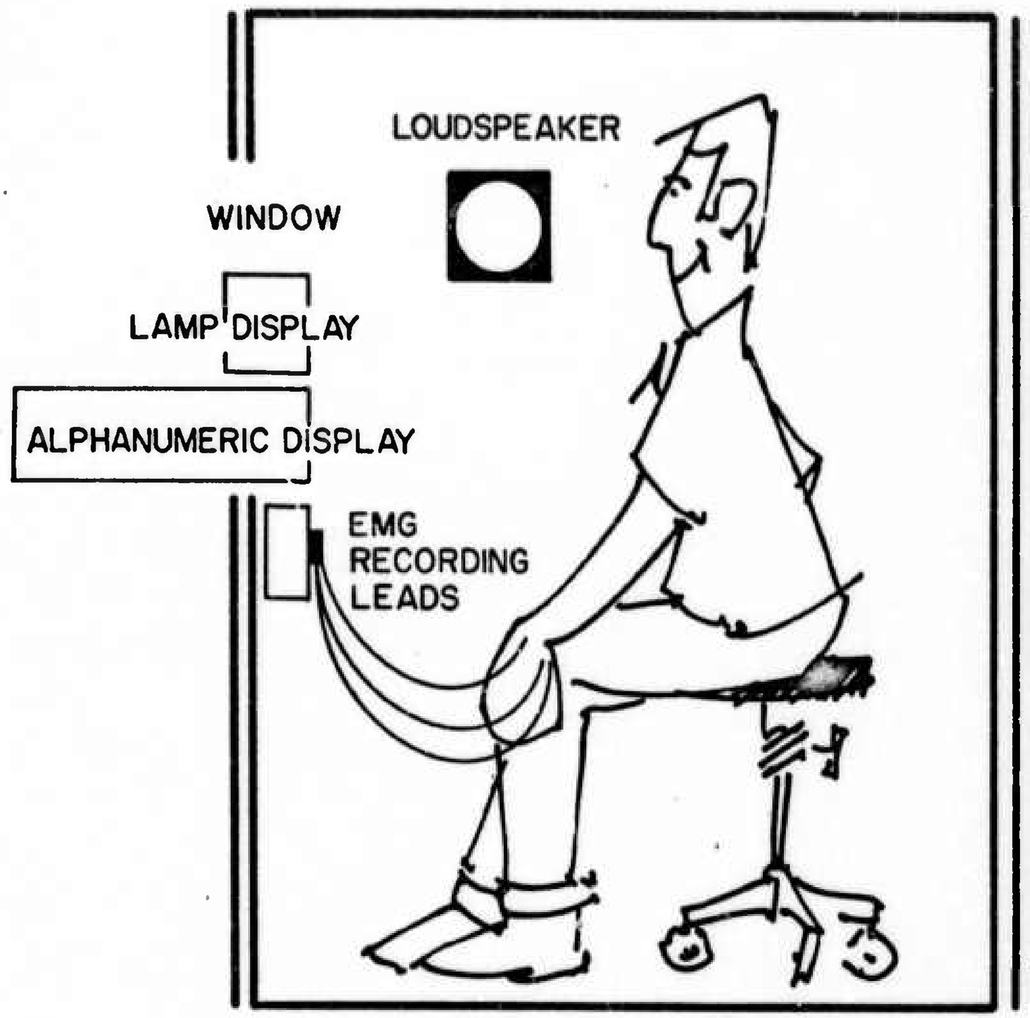
Fig. 7 Day four spelling performance in percent correct letters as a function of number of components and position in word.

Fig. 8 Latency to letter completion as a function of number of components in a letter and position in word across training days. Latency to response completion in msec.

Fig. 9 Latency histogram for two and three component letters in msec.

FIG. 1

PHYSICAL ARRANGEMENT



SOUND ATTENUATING ROOM

PHYSICAL ARRANGEMENT OF TRAINING FACILITIES

FIG. 2

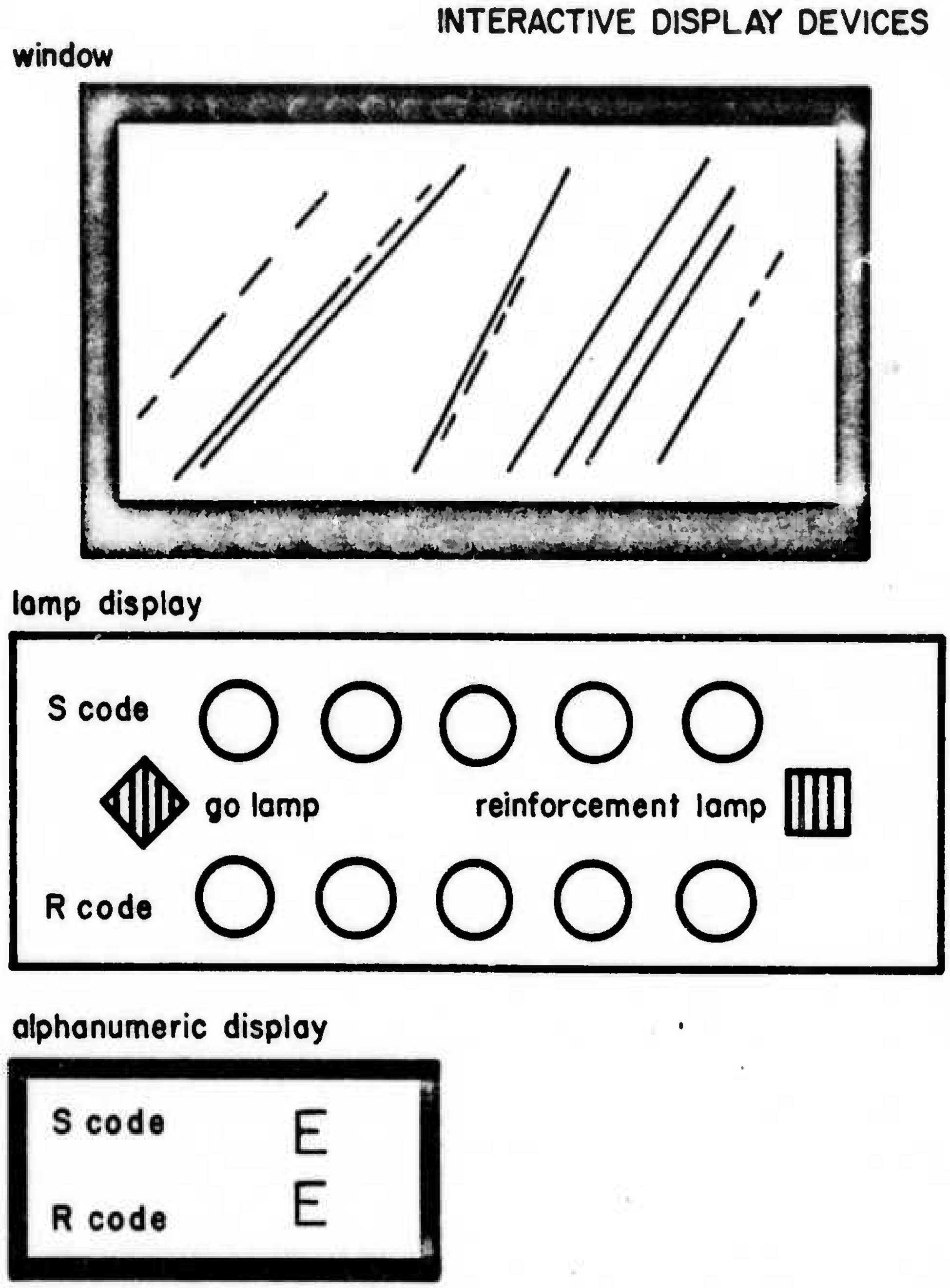
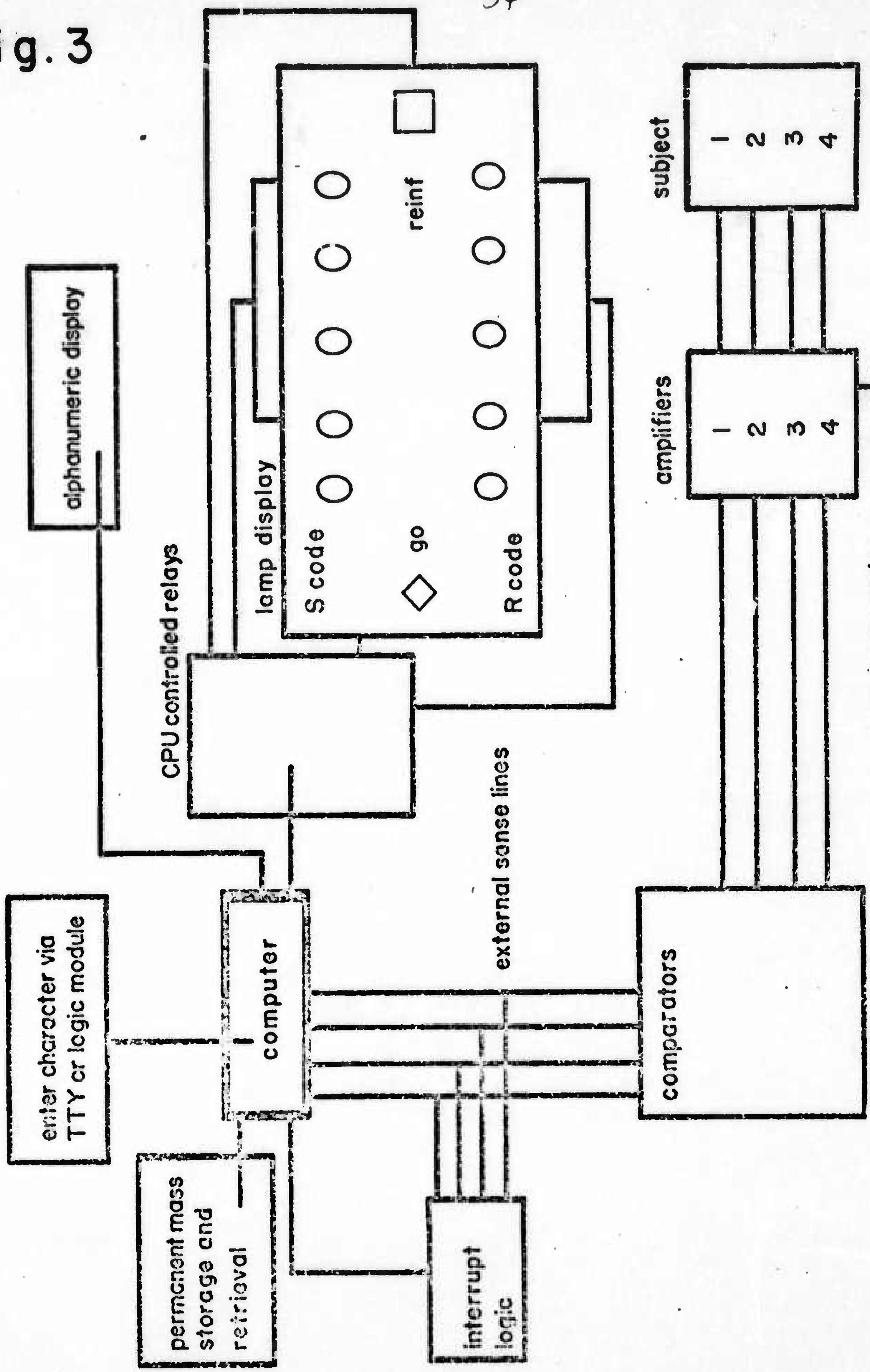

INTERACTIVE DISPLAY DEVICES
window
lamp display
S code
go lamp
reinforcement lamp
R code
alphanumeric display
S code
E
R code
E

Fig. 3



BLOCK SCHEMATIC B

Fig. 4

35

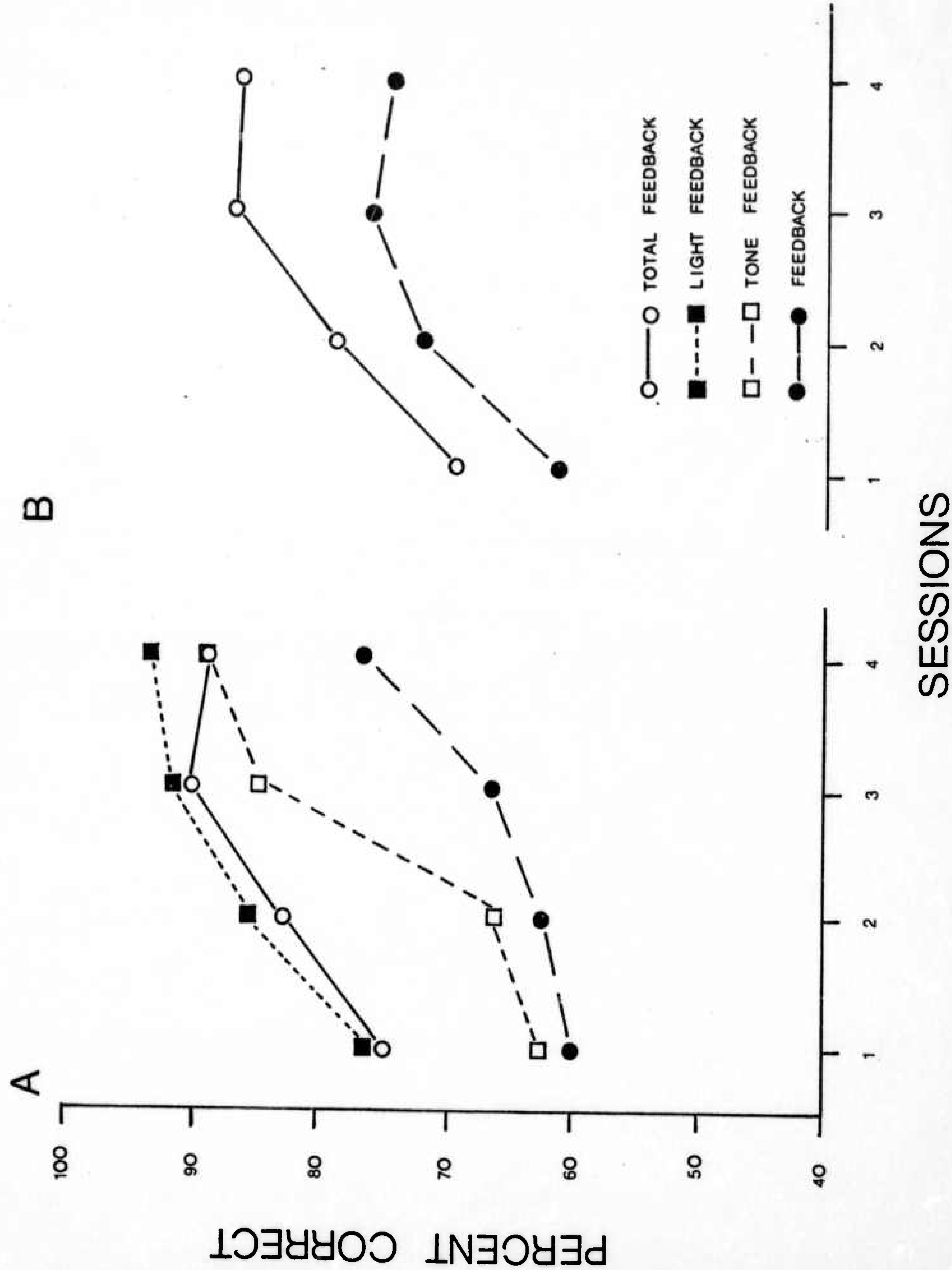

A
B
PERCENT CORRECT
SESSIONS
100
90
80
70
60
50
40
1
2
3
4
TOTAL FEEDBACK
LIGHT FEEDBACK
TONE FEEDBACK
FEEDBACK

Fig.5

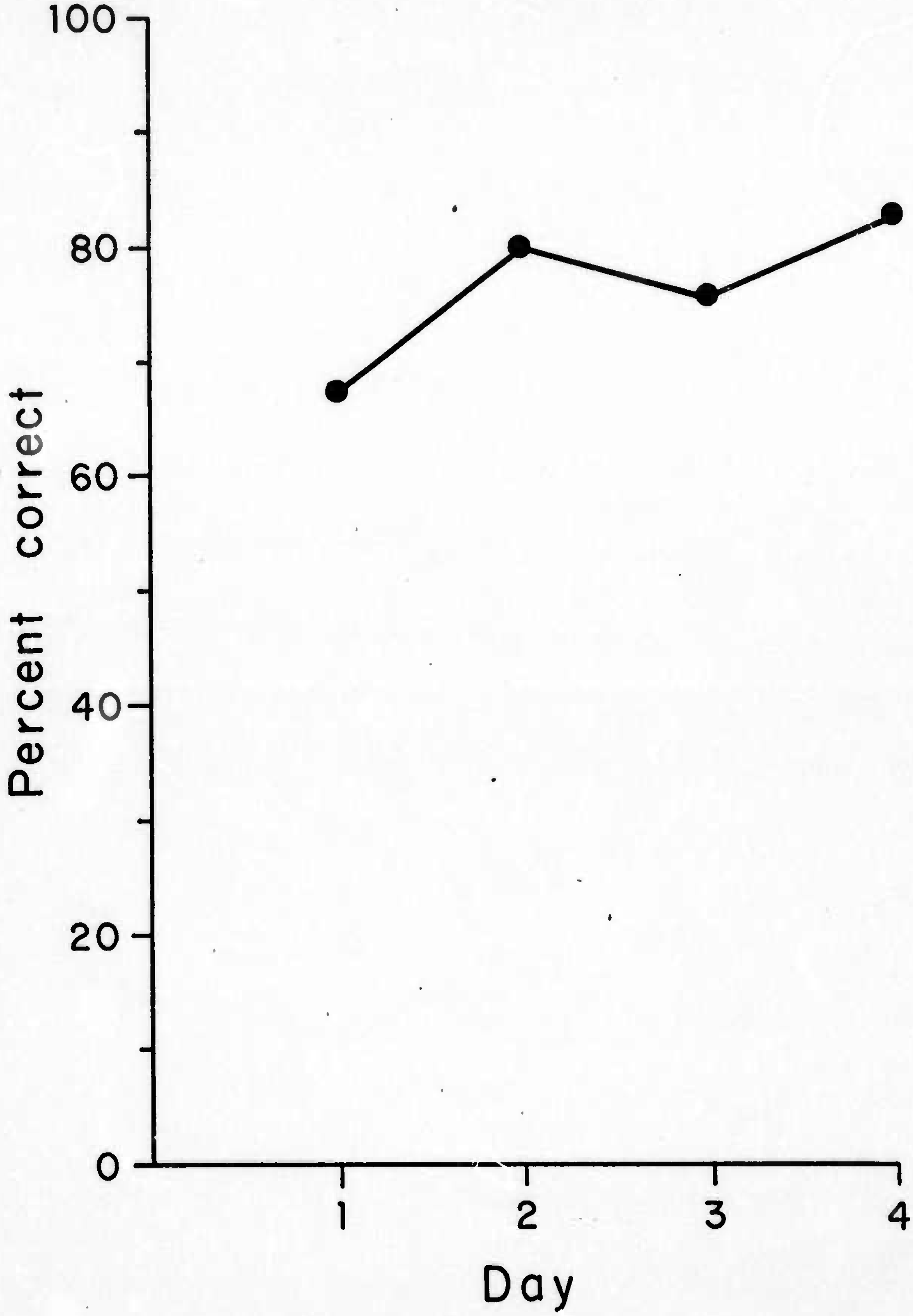


Fig. 6

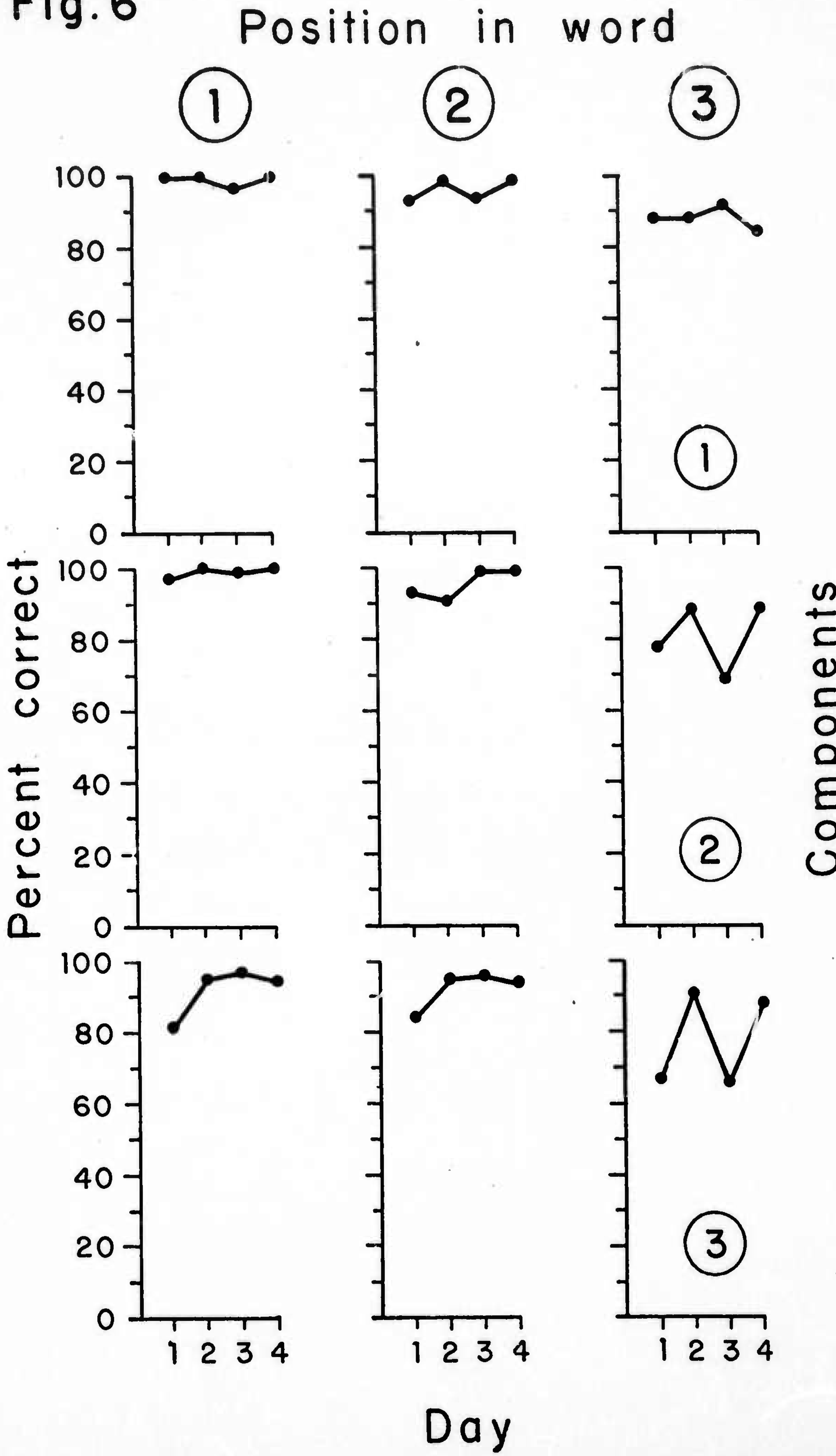
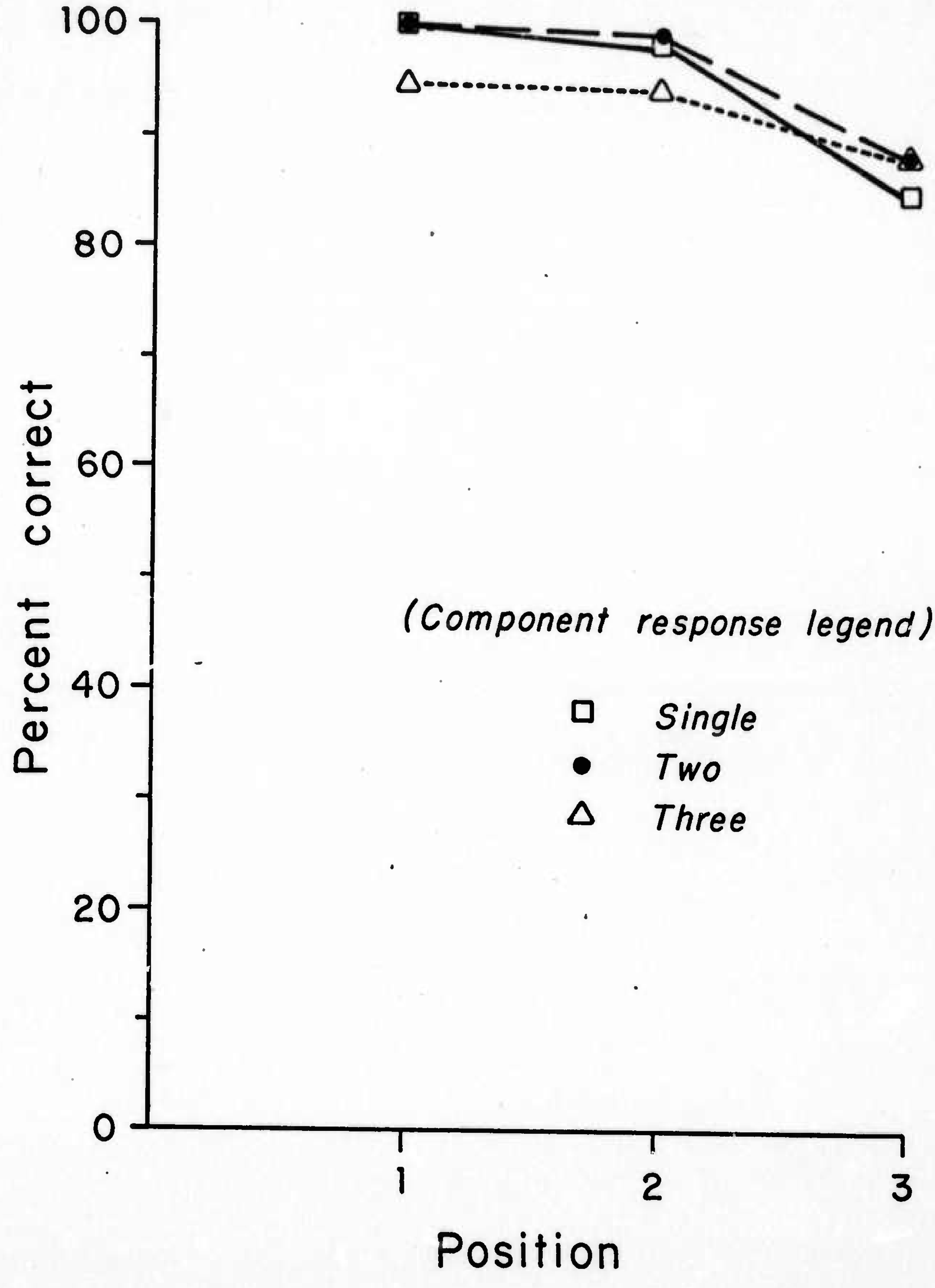

Position in word
1
2
3
Percent correct
100
80
60
40
20
0
Components
1
2
3
1 2 3 4
Day

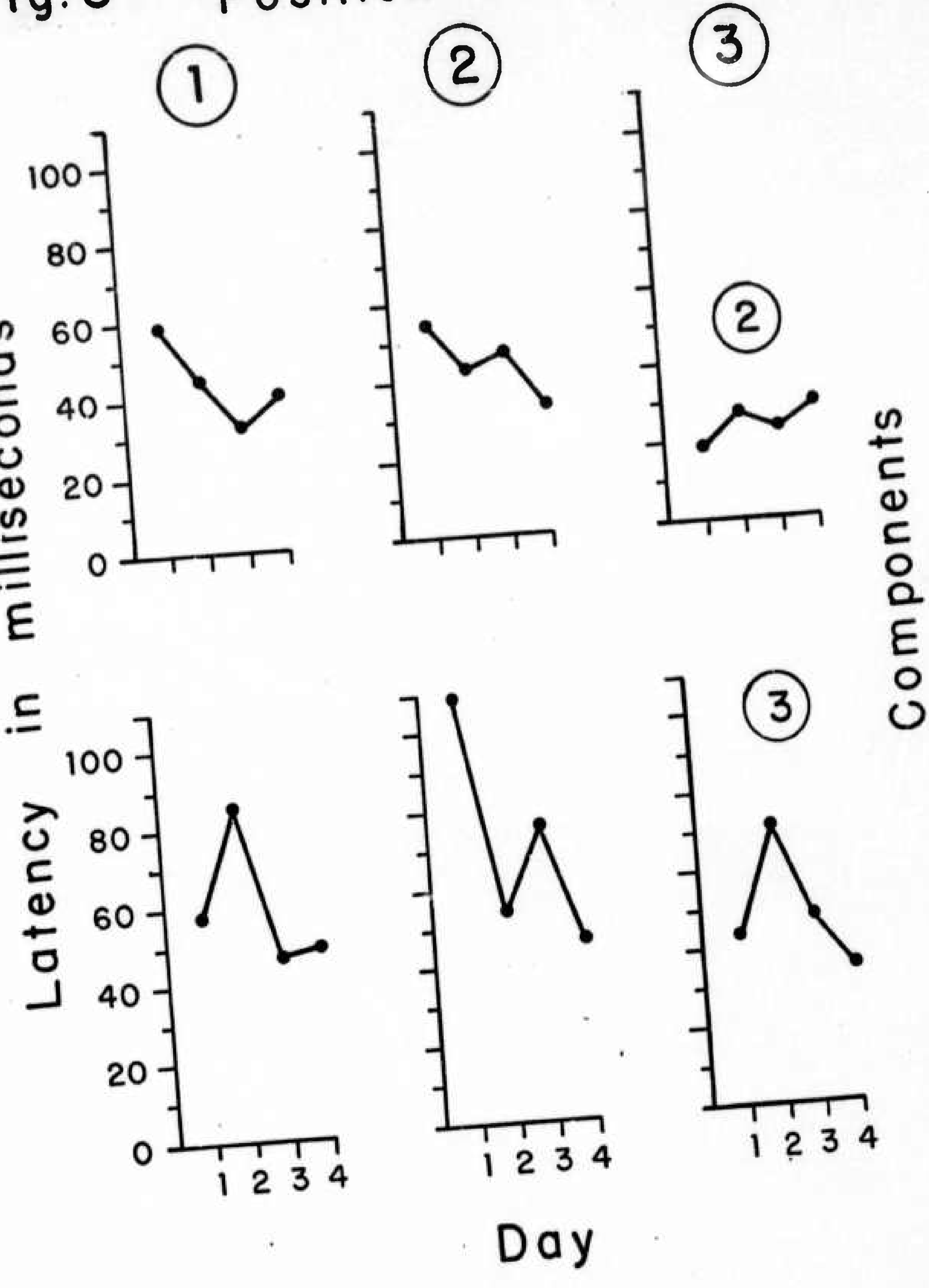
Fig. 7

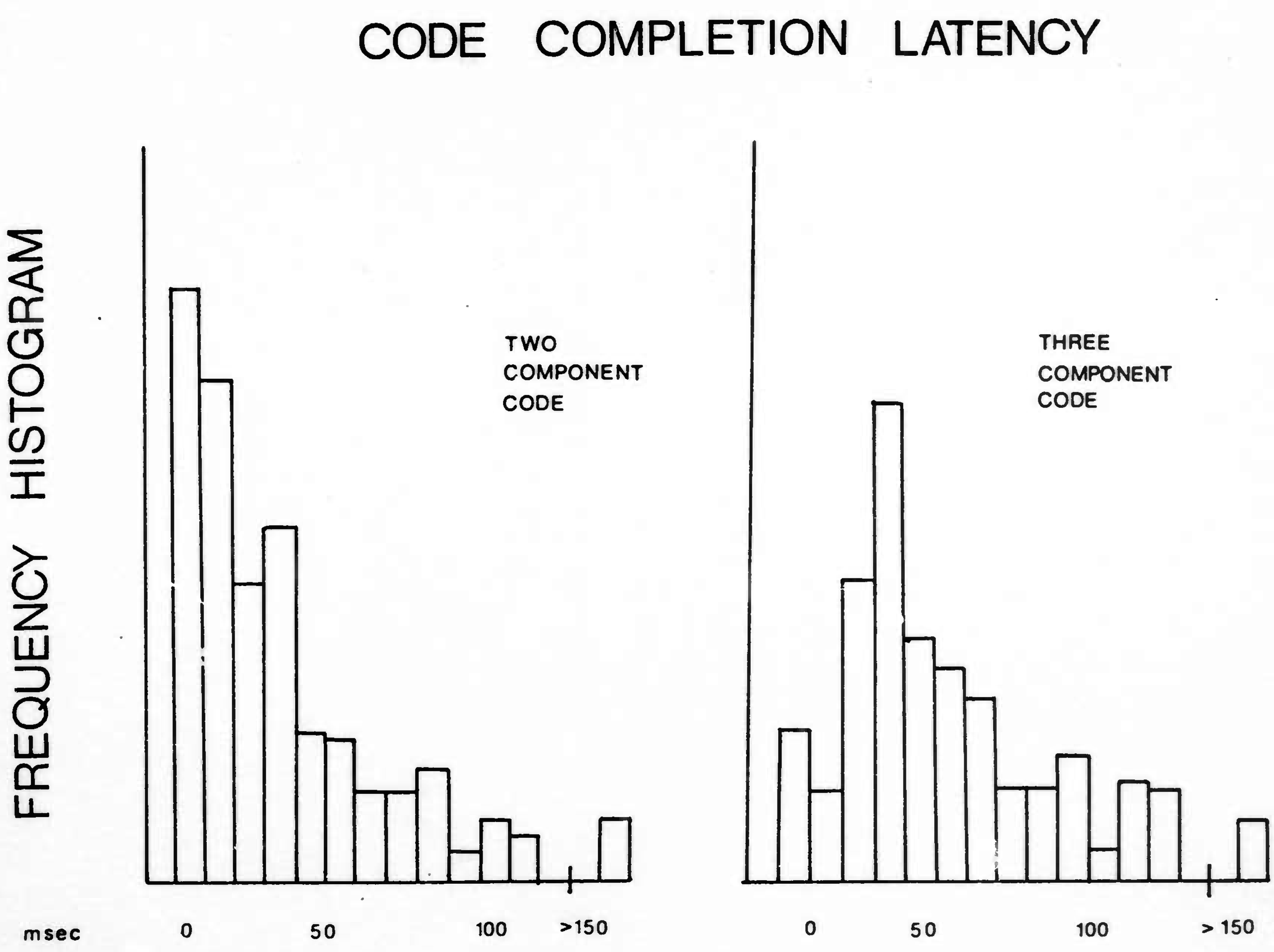
38



100
80
60
40
20
0
Percent correct
1
2
3
Position
(Component response legend)
Single
Two
Three

Fig. 8 Position in word





CODE COMPLETION LATENCY
FREQUENCY HISTOGRAM
TWO
COMPONENT
CODE
THREE
COMPONENT
CODE
msec
0
50
100
>150
0
50
100
> 150

Fig. 9

40