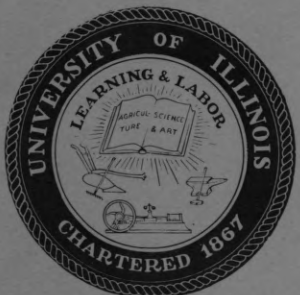


Coordinated
Science
Laboratory



UNIVERSITY OF ILLINOIS - URBANA, ILLINOIS

**HUMAN PERFORMANCE IN INFORMATION
TRANSMISSION
PART VI: EVIDENCES OF PERIODICITY
IN INFORMATION PROCESSING**

L.G. Augenstine

REPORT R-75

DECEMBER, 1958

**COORDINATED SCIENCE LABORATORY
(Formerly Control Systems Laboratory)**

UNIVERSITY OF ILLINOIS

URBANA, ILLINOIS

Reprint Prepared September 1962.

"The research reported in this document was made possible by support extended to the University of Illinois, Control Systems Laboratory, jointly by the Department of the Army (Signal Corps and Ordnance Corps), Department of the Navy (Office of Naval Research), and the Department of the Air Force (Office of Scientific Research, Air Research and Development Command), under Signal Corps Contract DA-36-039-SC-56695, Project 8-103A, D/A Project 3-99-10-101."

INTRODUCTION AND SUMMARY

This is the sixth and final report in a series dealing with man as an information transducer. The main interest of the Bio-Systems Group in all of these studies has been to define man's capabilities in terms which are usually associated with the description of machines. The need for such a description has arisen because of the necessity of designing data processing systems which employ the coordinated talents of both men and machines.

Information transduction requires at least three operations; data input, data processing, and responding. In the present study an attempt has been made to specify some of the properties associated with data processing. Subjects were presented a variety of tasks chosen so that (1) in the majority either a single response or very simple responses were required, (2) the stimuli consisted of simple and familiar symbols or situations, (3) each response could be formulated by making a sequence of simple unequivocal decisions, (4) each response required many such decisions, and (5) the tasks were self-paced.

Analysis of the response times indicated that the performance of these simple tasks is undoubtedly quantized in units of 100 msec. However, it is not clear if this is the fundamental quantum associated with data processing. Rather, this may represent a grouping of three more fundamental quanta of 33 msec. duration and within which one act of either data processing or input can be performed. Also there are indications that a 265 msec. periodicity--probably linked to eye movements--is associated with those tasks requiring vertical scanning.

MODEL

Stroud^{1,2} has postulated that man's actions are quantized into "moments" whose durations are greater than 50 or less than 200 msec. In a preliminary experiment we also obtained evidence that man's activities may be quantized.³ The preliminary assumption was that the time, T , taken to complete a simple task is the sum of the constant times, t , required for the individual operations necessary for transmission (i-inputing, p-processing, r-responding):

$$1) T = t_s + \beta t_i + \alpha t_p + t_r$$

plus a constant time, t_s , for accomodation, etc., at the start of each task. β and α are restricted to integral values.

Relation 1 would define a recurring delta function, displaced from the origin by $(t_s + t_r)$ and with a separation between the delta spikes of either t_i or t_p . However, the data had rounded maxima with diffuse rather than sharp distributions about the modal values. Therefore, to make allowance for this "lumpiness" the t 's of eq. 1 were modified so that instead of constants they represent average values for disperse rather than sharply peaked distributions:

$$2) T = \beta(t_i + \Delta_i) + \alpha(t_p + \Delta_p) + (t_s + t_r + \Delta_{sr})$$

In this equation

t_s is the average time needed for accomodation and those other processes preparatory to inputting and processing.

t_i is the average time needed to input each portion of data.

t_p is the (average) duration of the time quantum associated with the "unit act" of data processing.

t_r is the average time required for responding.

β is an integer; it is the number of portions of data input.

α is an integer; it is the number of "unit acts" required to perform the task.

The Δ 's represent the distributions associated with the various t's. In all the work to be reported the Δ 's were assumed to have Gaussian distributions which were characterized by the appropriate standard deviations, σ 's (see R-78).

The tasks employed in this study were designed specifically to search for periodicities (quantizations) of the order of 25-300 msec. The five criteria mentioned in the previous section were invoked in an attempt to restrict the study to those tasks in which t_s and t_r would be minimal and constant among trials (i.e., completely routinized tasks) and Δ_{sr} would have a peaked rather than a disperse distribution. (In such situations t_s and t_r would shift, and Δ_{sr} make slightly fuzzy the origin of coordinates, and therefore not interfere with an analysis of periodicities.) These precautions have been taken since the difficulty increases, and the efficiency of an analysis decreases, as the number of t's exhibiting periodicity increases.

If the inputting and processing of data can occur simultaneously rather than serially, β would have the single value of unity. If such is the case, or if as our data indicate t_i equals t_p , then detection is much easier.

EXPERIMENTAL METHODS

All experiments (except the one involving skeet shooting) were completely self-paced. Most displays consisted of printed letters or numerals on white cards, each individual run began with the display in viewing position in a darkened room. The subject was instructed to turn on a light (by means of an easy action 15 A. micro-switch) at his

leisure and to maintain illumination upon the display until completion of the assigned task. At that time he was to release the switch and immediately give his response. The time during which the switch was depressed was designated as the "display duration". This is a form of disjunctive reaction time. Except where noted an electric timer with scale divisions of 2 msec. and a stated accuracy of ± 3 msec. was read to the nearest 10 msec. Room illumination was controlled by the experimenter and was kept at a minimum level (which was just comfortable for reading) at all times except just before and during each run; this maintenance of general room illumination between displays was an attempt to minimize or at least keep constant, that portion of the reaction time devoted to accommodation.

Four general types of tasks were used: (1) those requiring a number of quite simple and straightforward decisions, a relatively large amount of scanning and a minimum of response effort; (2) those requiring little scanning but higher level data processing and little response effort; (3) those requiring considerable muscular response; and (4) scanning, processing, and responding were all minimized. The tasks we employed are described below and abstracted in Table 1.

(1) Scanning: Both vertical and horizontal displays--placed at 2 feet viewing distance--were used, in which the subject was to look for a particular symbol. In one series a sequence of letters and numerals were mixed and the subjects started either at the top or the left-hand side of the sequence and scanned down or to the right until he found the first numeral. This was identified verbally immediately after releasing the light switch. The number of letters preceding the first number was randomized and the subject was told to expect from 0 to 25 preceding letters. Some subjects were shown a group of such cards in

TABLE 1

Summary of experimental types and designations and descriptions of the tasks.

Type	Symbols	Description of Task
1. Scanning	SV	Recognition of first letter in a vertical list of mixed numbers and letters--all positions equiprobable.
	SHE	Recognition of left-most letter in a horizontal list of mixed numbers and letters--all positions equiprobable.
	SHN	Same as SHE except all positions were not equiprobable.
	SO	Recognition of either 10 or 01 in a vertical column of 00 and 11 symbols--all positions equiprobable.
	SA	Addition of vertical columns of numbers.
	SLP	Looking at pictures (Buswell ⁴).
	SD	Detection of unique dial within an ensemble.
2. Minimal scanning	WS4	Synthesis of the 4-letter English word from a scrambled tetragram.
	WS3	Synthesis of the 3-letter English word from one of its scrambled permutations.
3. Muscular response	MRS	Skeet shooting.
	MRT	Typing random text.
4. All factors minimized	NN	Null response.

which the numerals occurred at each position an equal number of times; for others the first numeral occurred at the third, eighth, thirteenth, eighteenth, and twenty-third position 25 times each and at the rest of the positions six times each. These experiments are designated:

SV - vertical column each position equiprobable

SHE - horizontal column each position equiprobable

SHN - horizontal column positions not equiprobable

In most experiments displays were placed on a stand in front of the S's and illumination was provided by two 60-watt bulbs. In SHE and SHN a Gerbrand Tachistoscope was used.

In a similar experiment, SO, subjects scanned vertical columns containing 00 and 11 as basic symbols to detect either 10 or 01 symbols. There were 26 such pairs of numerals and the 01 or 10 symbol occurred with equiprobability at all of the positions. In addition, one-fifth of the cards contained only 00 or 11 pairs. For these the subjects were to give the single response "Negative".

Another task, designated SA, which required slightly more involved data processing than the above experiments but also required considerable scanning was the addition of vertical columns of numbers. The displays consisted of a column of ten numbers (either one or two digits) so that the sum was either 100 or less or 1000 or less.

Buswell has reported on the duration of eye fixation when people look at pictures.⁴ Data from nine of his subjects were analyzed and are designated as experiment SLP.

In addition data from 20 subjects were made available by Dr. Virginia Senders, involving the scanning of an ensemble of airplane dials to find a single dial whose setting was different from the rest. Strictly speaking these data were not comparable to the above scanning

experiments in that the experiments were not self-paced, that is, the onset of the light was not controlled by the subject. This experiment was designated SD.

(2) Minimal Scanning (Word Synthesis): In one series, designated WS4 familiar four-letter English words were scrambled so as to form meaningless tetragrams. The displays were constructed from regular anagram letters placed on a non-reflecting black background. The subject was instructed to maintain illumination on the display until he could recall an English word which could be constructed from the four letters. The displays when in position for viewing were at eye level, six feet from the subject. A small neon glow lamp was placed directly beneath the second letter from the left to aid in fixation; otherwise conditions were the same as in the scanning experiments. It should be emphasized that more than one response was possible; for instance, the words cane and acne can be formed from the same tetragram.

In a second series (WS3) the three-letter English words were selected from Thorndyke. From this list of 270 words those with two letters the same or with two meaningful permutations of the three letters were discarded. Displays of the five non-meaningful permutations were made using one-inch letters from an ordinary printing set. These cards were then screened by six people in the Bio-systems group for possible permutations which suggested a different solution than the intended one, e.g., VAT was discarded because of the obvious implications of the permutation TVA, SEA was discarded because the permutation SAE suggested one of the fraternities on the campus, etc. A total of 51 words were rejected on the basis of the above two criteria and all five permutations of the rejected words were discarded. This gave a group of 220 words or a total of 1100 stimuli. These were shuffled

to produce a near-random order and then all successive cards which were permutations of the same word were further separated. These stimuli were placed in a slot in the backside of a 3 x 3 x 3-foot box which had a one-foot square opening in the front. Two 24"-long 60-watt incandescent lamps were placed in the front two corners of this box. When the subject depressed his switch the room lights were extinguished and the lights in the box turned on. The room lights were arranged so that they shone onto a pale green wall directly behind the exposure box and did not permit the subject to read the display before depressing his key. The viewing position was specified by requiring the subject to place his chin in a fixed support 10 feet from the display.

(3) Muscular Response: Skeet shooting (MRS) is quite different from the above two types in that it was neither self-paced nor did it consist solely of scanning and data-processing; rather, considerable muscular response was also involved. In each test the subject indicated when he was "ready" and the mechanism controlled by the experimenter for electrically tripping the skeets produced an electrical impulse which was recorded on one channel of a Brush recorder. A nearby microphone produced an impulse in the other channel of the recorder when the gun was fired. The elapsed time between the two impulses was used as the measure of the response time. Two subjects, one a distinct novice and the other an expert, each fired at 88 skeets.

Data selected from the typing of random texts (R-70) have been designated MRT. These data were obtained using an electric typewriter modified so that the striking of any of its keys gave an electrical pulse on a Brush recorder. The interpulse time was thus a measure of the decision time associated with the individual letters. The S's were three young women typists of average professional skill.

(4) All Factors Minimized: In an experiment designated NN the subject was instructed to depress a key, at his leisure, which would turn on the usual experimental light and to release it at his leisure. The idea of this experiment was to determine if the quantizations observed for the earlier and more complex experiments might indicate that a subject's muscular responses were closely tied to an "internal metronome". The length of time during which the key was depressed was recorded and this distribution was analyzed for periodicities in a manner similar to the other experiments.

METHODS OF ANALYSIS

Four general methods of analysis were used: (1) the various histograms were tested for randomness, i.e., an attempt was made to determine if the peaks and troughs could be accounted for by random fluctuations in otherwise smooth trends; (2) the data were tested for periodicities by the use of the techniques of autocorrelation and power spectra; (3) Monte Carlo methods were used to generate data, according to eq. 2, simulating that obtained from the S's in our tests; (4) attempts were made to account for the human histograms as the sum of Gaussians with equal σ 's and equally separated modes.

(1) The test for randomness suggested by Wallis and Moore⁵ was used. In this test the set of N values from a response time histogram was transformed into a set of (N-1) +, -, +, -, etc., values. For such a set derived from a random sample the expected number of sets having d like signs in sequence is given by the relation

$$(3) n_d = \frac{2(d^2 + 3d + 1)(N - d - 2)}{(d + 3)!}$$

A χ^2 test comparing the actual distribution to that predicted by

relation 3 gives the probability that a sequence of random numbers would exhibit the observed distribution.

(2) Autocorrelation and power spectrum analyses were used to search for periodicities. These methods, their applications, and limitations for the analysis of the type of data dealt with in this report have been discussed elsewhere (R-78)⁶; and therefore, will only be summarized here.

The autocorrelation function (AC) in the form used by Seiwel⁶ is given by

$$(4) R_k = \frac{\overline{x_i \cdot x_{i+k}} - \overline{x_i} \cdot \overline{x_{i+k}}}{\sigma_i \cdot \sigma_{i+k}} \quad \begin{array}{l} k = 0, 1, 2, \dots, m \\ i = 1, 2, 3, \dots, N-k \end{array}$$

where

R_k is the k th value of the AC function.

x_i is the value of the i th interval of the histogram; i.e., x_i is the frequency with which response times of i intervals (of 10 msec.) longer than the shortest response are observed.

$\overline{x_i \cdot x_{i+k}}$ is the average of the $(N - k)$ products of the form $x_i \cdot x_{i+k}$ for $0 \leq i \leq N-k$.

$\overline{x_i}$ is the mean of the x_i 's for $0 \leq i \leq N-k$.

$\overline{x_{i+k}}$ is the mean of the x_i 's for $k \leq i \leq N$.

σ_i is the standard deviation of the x_i 's for $0 \leq i \leq N-k$.

σ_{i+k} is the standard deviation of the x_i 's for $k \leq i \leq N$.

The cosine series representation of the Fourier transform of the AC function in eq. 4 was used in the spectral density function; it is similar to the correlation expression suggested by Tukey.⁷ This form was chosen since it contains terms to help correct for the non-constant average amplitude existing in the histograms. The description of the operations involved is:

$$(5) U_p \approx \sum_{k=0}^m b_k R_k \cos kp \pi/m; p = 0, 1, 2 \dots m$$

$$(5a) b_k = 0.52 + 0.46 \cos k \pi/m$$

where U_p is the p th coefficient of the Fourier cosine series representation of the autocorrellogram, and

b_k is a smoothing function suggested by Tukey^{7,8} to make peaks in U_p more pronounced.

In addition to the power spectra, second order autocorrelations (designated AC^2) were performed on many of the first order autocorrelations (AC) in which it appeared that more than one periodicity occurred. It was hoped that multiple periodicities could be separated by such a procedure.

(3) Attempts to synthesize data according to eq. 2 so as to duplicate the behavior of the S's have been discussed extensively in R-78. A given set of data was synthesized as follows: i) constant values were given to the t's, Gaussian distributions were assigned to α and β and a σ was specified for each Δ ; ii) single T values were obtained by substituting into eq. 2 a value--which had been selected by Monte Carlo methods--from each α, β , and Δ distribution; iii) the set of N generated response times was then treated the same as those obtained from our S's.

(4) When initial moderate success was obtained in duplicating the human results with the synthesized data an attempt was made to "fit" histograms of human data by treating them as the sum of a number of Gaussian distributions. The histogram values were fitted precisely by allowing the positions and standard deviations of the individual modes to vary slightly. The average values of the separation and standard deviation of the modes was then used in the Monte Carlo generation

scheme. The standard deviations and locations of the individual modes were determined by plotting the cumulative of each fitted Gaussian on "probability paper".

RESULTS

(1) The Wallis and Moore (WM) test for randomness was applied to data selected from most of the scanning experiments (see Table 2) and to two sets of random numbers--one set was obtained by taking the last digit from individual phone numbers in the Chicago phone book and the other from a regular table of random numbers. When the WM test was applied to the random number sets it indicated that the probability that a sequence of random numbers would exhibit the same distribution was of the order of .15 to .20. When this same test was applied to data from the scanning experiments the probability was always much less than 10^{-3} . This indicates that the response time histograms do not represent data obtained from processes which are based upon random procedures.

(2) The conclusions presented in the preliminary report ³ are supported by the autocorrelation (AC) and power spectrum (PS) results summarized in Tables 2 and 3--portions of which are plotted in figs. 1-4. They indicate that a periodicity of 100 msec. is associated with the performance of simple laboratory tasks by a large fraction of our subjects. In addition, a periodicity of the order of 250-310 msec. may be observed if the performance of the task requires vertical scanning. Further the results suggest that the 100 msec. periods may actually be composed of two 50 msec. or 33 msec. components.

Although 100 msec. appears to be the strongest period (for instance, see fig. 4 in which 21 power spectra obtained from 6 subjects

and 6 experimental conditions have been averaged) peaks corresponding to 50 and 33 msec. also occur regularly. The weight in those peaks may be misleading since a strong 100 msec. periodicity of Gaussian wave form will produce maxima corresponding to 50 and 33 msec. (see R-78); in the PS these correspond to first and second harmonics of the fundamental 100 msec. peak. Although the 100 msec. periodicity is the more prevalent, the 50 msec. period predominates in some cases, e.g., subject Au in experiment WS4 or, subject Sr in experiment SA, and subject Bl in experiment SHN. Thus, in such cases the power in the 50 msec. peak must represent a true periodic component.

The data in figs. 1-4 provide an insight into the significance of the various entries in Tables 2 and 3. Those in plots 1A-1E are from subject Sr in 3 experiments (SO, SA, and WSH) and those in plot 1F represent pooled data from subjects Sr and Va for skeet shooting (MRS). Results from SHN for individual subjects (Br, Bl and Hi) are shown in figs. 2 and 3; earlier data for subject Au are on p. 221 of a previous report.³

The increased number of cards in SHN for which 3, 8, 13, 18, or 23 numbers preceded the first letter permitted a measure of the average time devoted to processing a single letter sufficiently to decide it was not a number. From the few cases available, the time per symbol seems to decrease as the number of preceding symbols increases. An attempt to make a linear plot through the modal values is shown in fig. 3A. Although it gives an admittedly poor fit, it can be used to provide an estimate of a general average value. For subject Hi it is 61 msec/symbol, for subject Br 65 msec/symbol, and for subject Bl 72 msec/symbol.

TABLE II

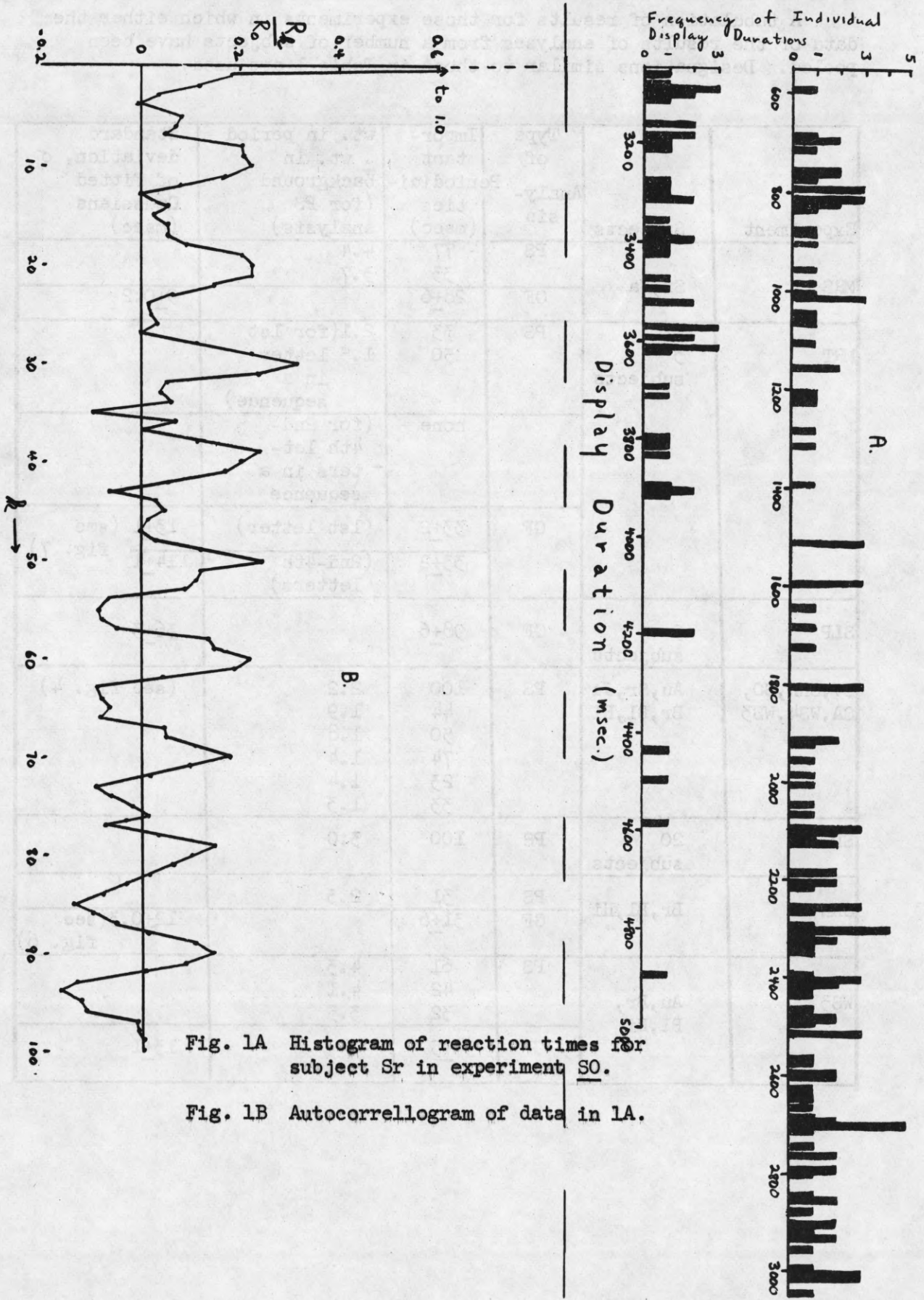
A tabulation of experimental results for individual subjects according to the experiments in which they participated. The analytical procedures used on each subject's data are listed by initials (Wallis and Moore, Autocorrelation--both first and second order, Power Spectrum, Synthesized Data, and Gaussian Fitting). The most important periodicities are listed in order and, if a PS analysis was performed, the weight associated with the predominant periodicity divided by the weight of the background is listed in parentheses.

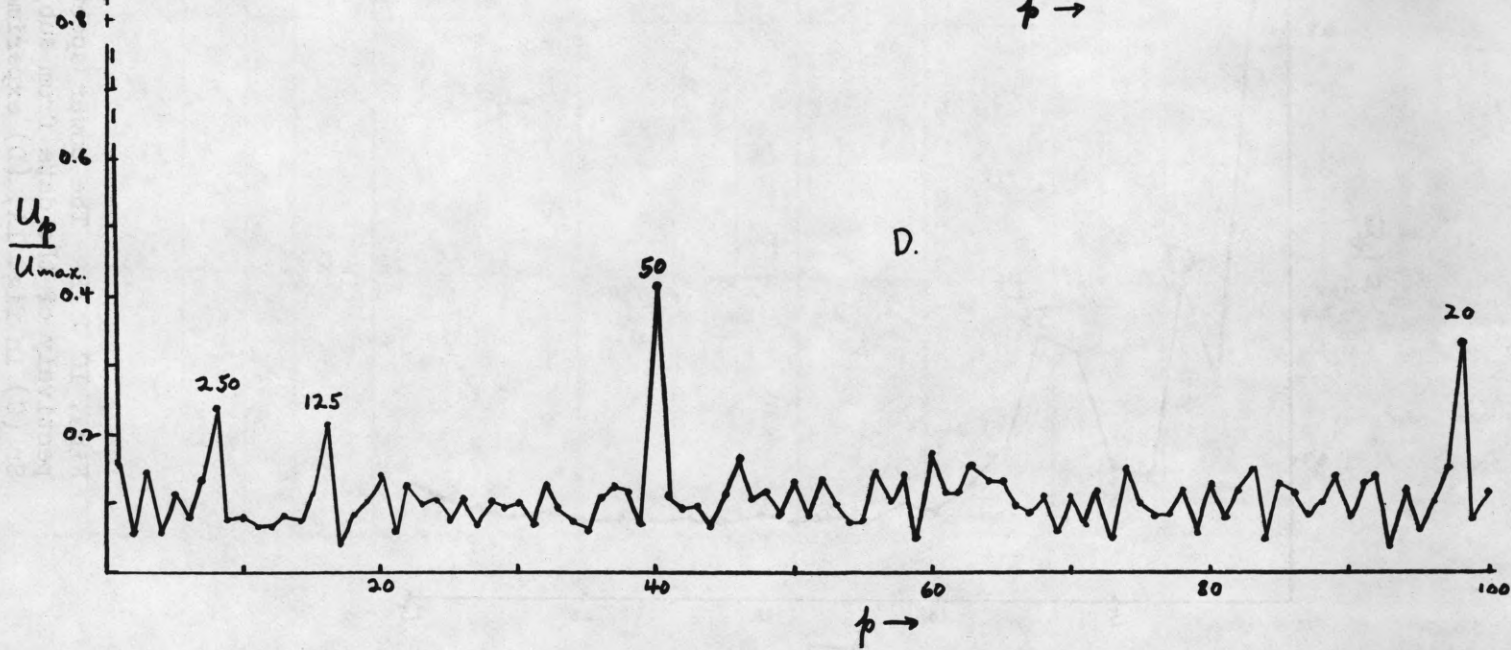
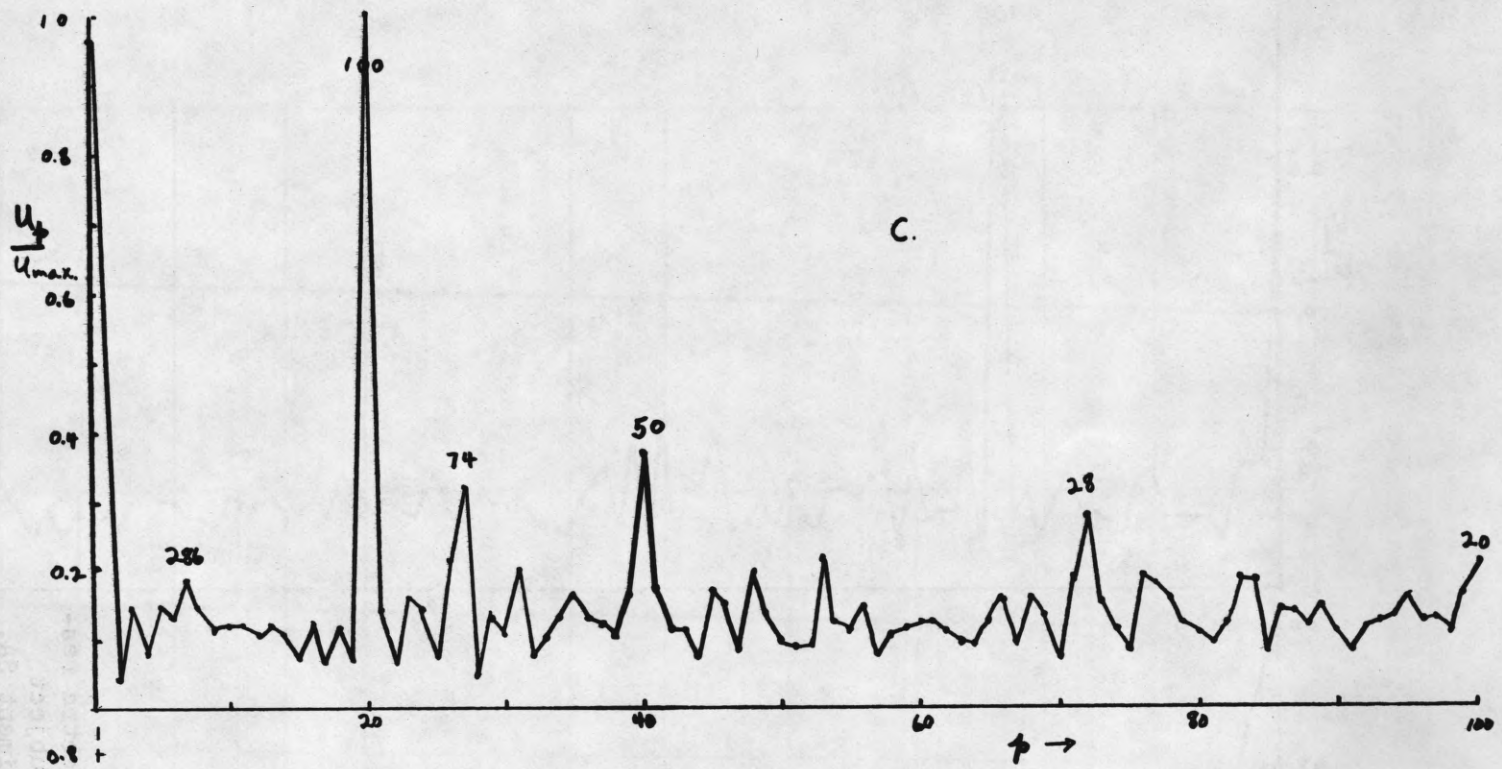
Subject	SV	SHE	SHN	SO	SA	WS4	WS3	NN
Au	WM, PS, AC ² 267(7) 100 50			WM PS 100(3.1) 286 35		PS 50(6.6) 100 30	PS none	AC AC ² none
Sr				PS 100(12.5) 50 74	PS 50(4.1) 20 250	PS 100(8.5) 45		
Ja		WM PS 100(8.5) 50 36		WM PS 100(11) 50 74	PS 100(6.5) 50 250	PS 100(1.9) 25 53		
Br			PS 100(5.0) 33 200				WM, PS 500(4.3) 250 35	
Bl			WM, PS 50(3.1) 400 39				PS none	
Hi	PS 33(3.4) 250 22		PS 33(2.8) 100 400				PS none	
Os	AC 310 110				AC, PS 100(2.6) 285 50			AC (50?)
Tw	AC ² 60 780							AC AC ² (60?)

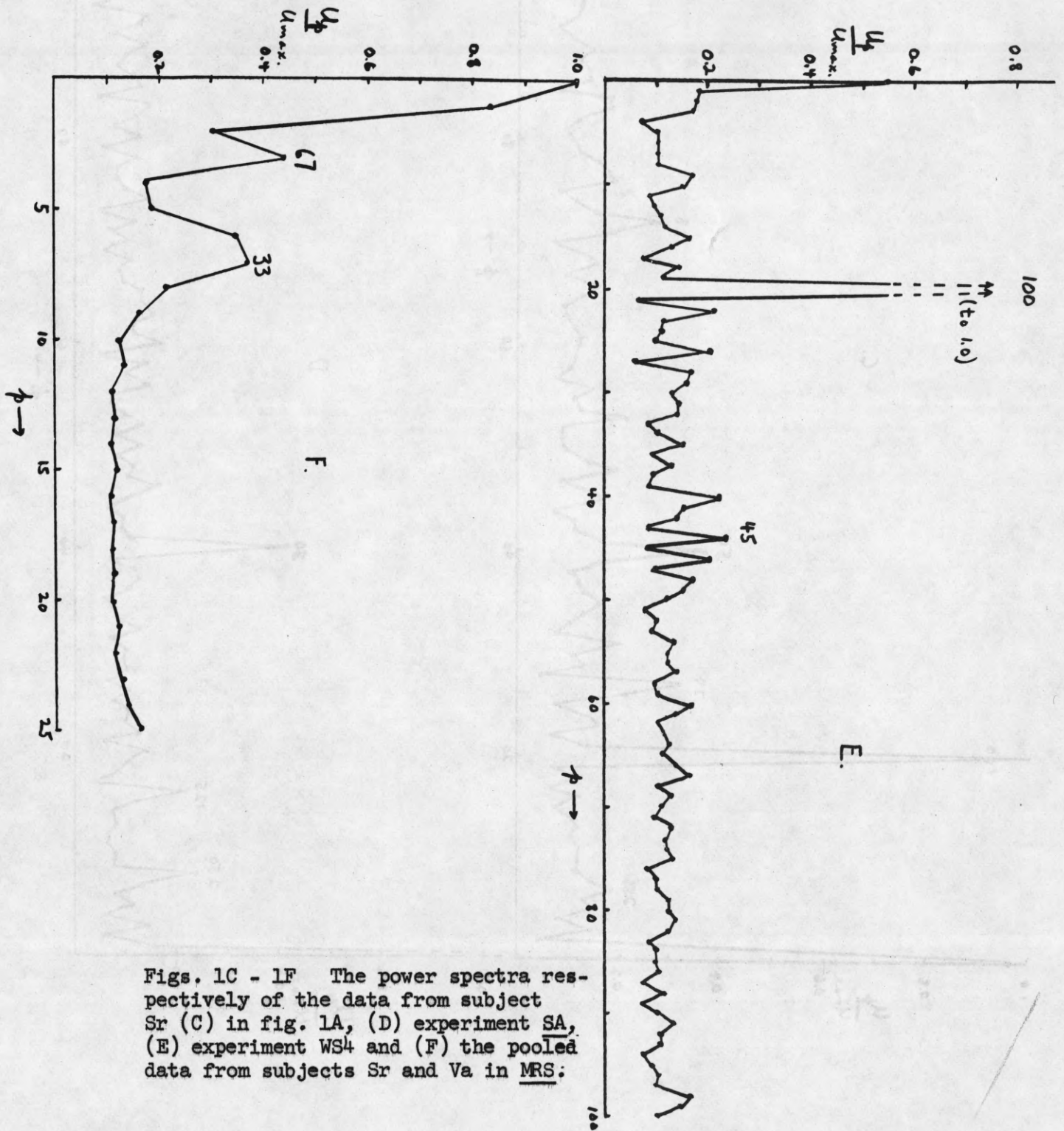
TABLE 3

A tabulation of results for those experiments in which either the data or the results of analyses from a number of subjects have been pooled. Designations similar to those in Table 1 are used.

Experiment	Subjects	Type of Analysis	Important Periodicities (msec)	wt. in period . wt. in background (for PS analysis)	Standard deviation, σ of fitted Gaussians (msec)
MRS	Sr, Va	PS	77 33	4.4 3.7	
		GF	28+66		9+0.2
MRT	3 subjects	PS	33 50	2.1(for 1st 1.5 letter in a sequence)	
			none	(for 2nd- 4th let- ters in a sequence)	
		GF	33+2	(1st letter)	13+1 (see fig. 7)
			33+2	(2nd-4th letters)	14+1
SLP	9 subjects	GF	98+6		36+3
SV, SHN, SO, SA, WS4, WS3	Au, Sr, Ja Br, Bl, Hi	PS	100 44 50 74 23 33	2.2 1.9 1.8 1.4 1.4 1.3	(see fig. 4)
SD	20 subjects	PS	100	3.0	
SHN	Br, Bl, Hi	PS	31	2.3	
		GF	31+6		12+0.3 (see fig. 6)
WS3	Au, Br, Bl, Hi	PS	61 42 32	4.3 4.1 3.5	
		GF	34+5		13+1







Figs. 1C - 1F The power spectra respectively of the data from subject Sr (C) in fig. 1A, (D) experiment SA, (E) experiment WS⁴ and (F) the pooled data from subjects Sr and Va in MRS.

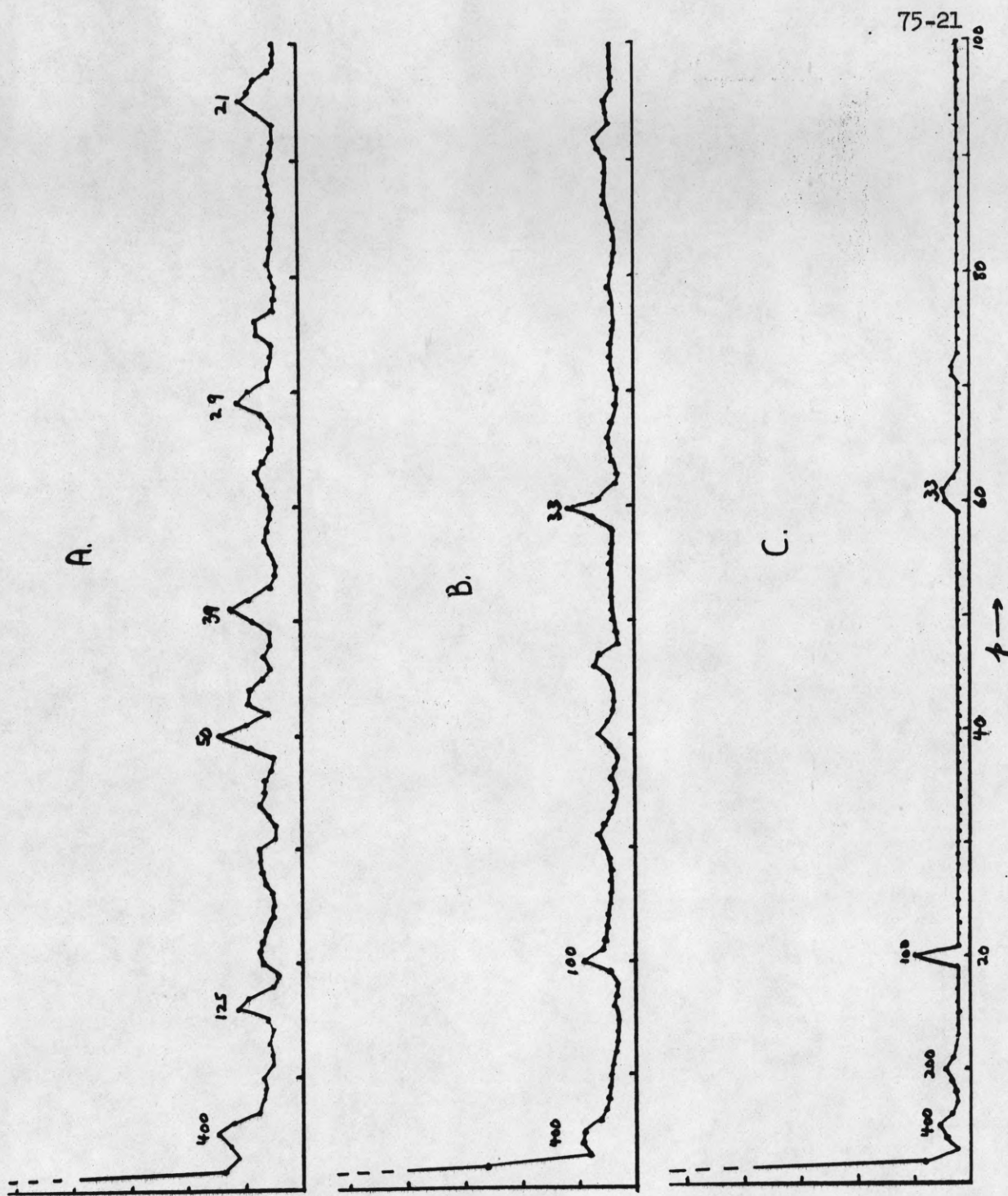


Fig. 2 The power spectra of data
 from (A) subject Bl, (B) sub-
 ject Hi and (C) subject Br in
 experiment SHN.

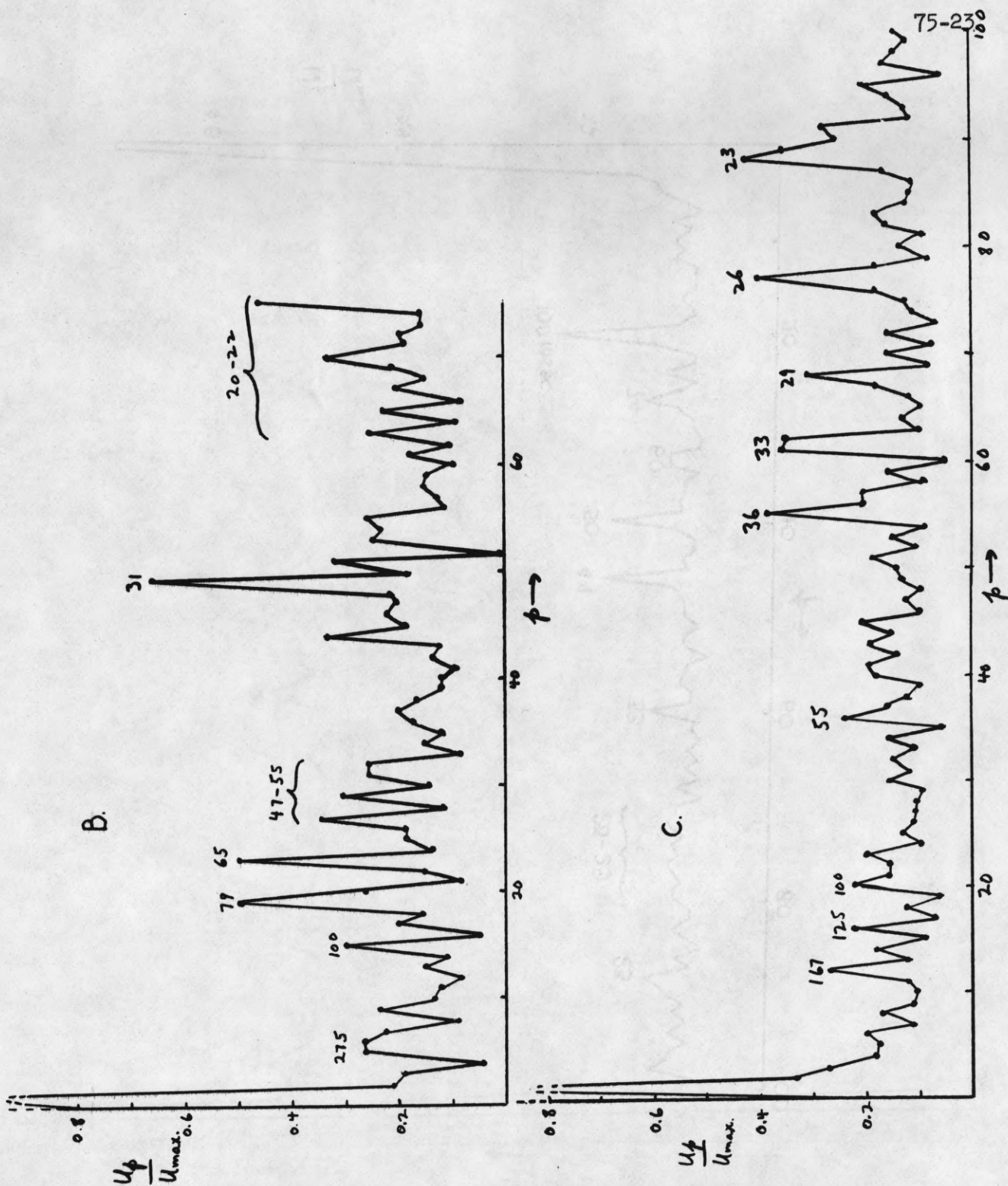


Fig. 3 (A) Histogram of reaction times for subject Hi in SHN; (B) PS of data from position 8 and (C) PS of data from position 18. See text for a more complete discussion of the elements of this figure.

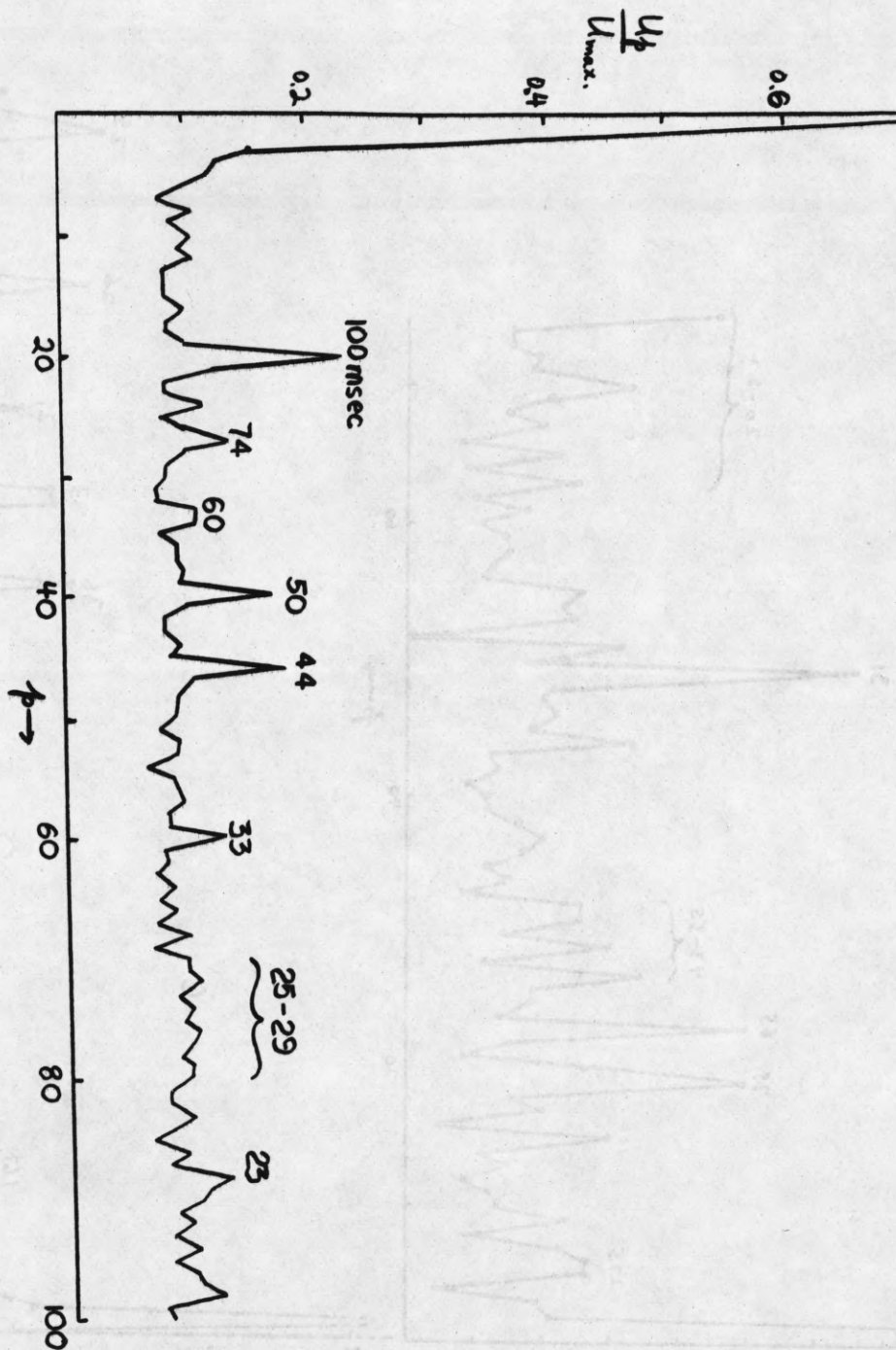


Fig. 4 A composite PS constructed by normalizing the sum of 21 PS obtained from 6 subjects and under 6 experimental conditions.

With the exception of experiment WS3 (in which essentially no periodicities were detected), the results (figs. 2 and 3) for SHN represent the lowest absolute weight associated with the various PS analyses listed in Table 2. The essentially random results obtained in experiment WS3 were unexpected considering the regularity with which the 100 msec. periodicity was detected in other experiments. This experiment was designed to be the most carefully controlled and the task most rigorously defined of those run. However, it was more difficult than anticipated so that the 1100 response times ranged from 50-6000 msec. As mentioned previously (and in R-78), such a low density of data makes a successful power spectrum analysis very difficult. Even pooling the data from 4 subjects gave no strong indication of a 100 msec. period, although indications of 61 and 32 msec. periods were obtained.

Analysis of the MR series of experiments was complicated not by low data density but rather by the fact that most of the data were sharply peaked. This was particularly true when data from individual subjects were analyzed. However, pooling the data from a number of subjects usually produced a range over which a limited power spectrum analysis could be made; those results are listed in Table 3.

(3) Once strong evidence of a 100 msec. period was obtained from the AC and PS methods, efforts--elaborated in R-78--to synthesize data according to eq. 2 were begun. In all cases the power spectra of synthesized data were compared to those of human data--the object being to match the two as closely as possible. Attempts were made to duplicate the PS from individual sets of data as well as pooled-average power spectra. Only the latter will be cited since roughly equal success was obtained in both cases. An acceptable duplication of the

human PS by the generated data was not produced by setting $t_p = t_1 = 100$ or 50 msec. The most satisfactory results were obtained--see Fig. 5A-- when $t_p = t_1 = 33$ msec., $\sigma_{sr} = 13$ msec., $\sigma_p = 0.2$ msec. and α was assigned the distribution shown in fig. 5B. Although the power in corresponding peaks is not the same in the two curves, all of the major peaks in fig. 4 are represented in fig. 5A. Since fig. 4 is an average from 21 sets of data, all of which would not be expected to have exactly the same α -distribution it is not surprising that a single distribution for α does not give perfect duplication. The general shape of α was obtained both by constructing a smoothed "envelope" through the maxima in the human histograms and from the values of the maxima obtained by the Gaussian fitting procedures. The superimposed "fine structure" of α was introduced to increase the power in the 100 msec. peak when the main period was set equal to 33 msec.

No attempt was made to duplicate those results in which 265 msec. peaks as well as 100 msec. were found since we doubted that the former were associated with processing mechanisms.

(4) The results in figs. 6 and 7 are typical of those obtained when the response histograms were treated as the sum of equally spaced Gaussians all having the same standard deviations. In all cases tested--except those in experiment SLP--the modes were separated by very close to 33 msec. and had standard deviations of about 13 msec. It would have been impossible to detect a 33 msec. period in the SLP data since those time intervals were measured in units of 30 msec.

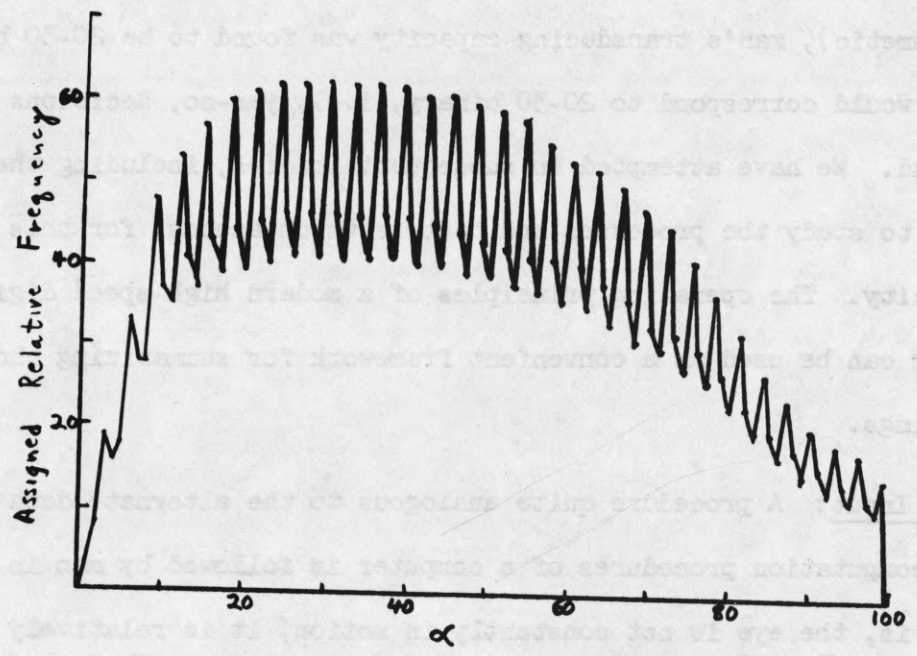
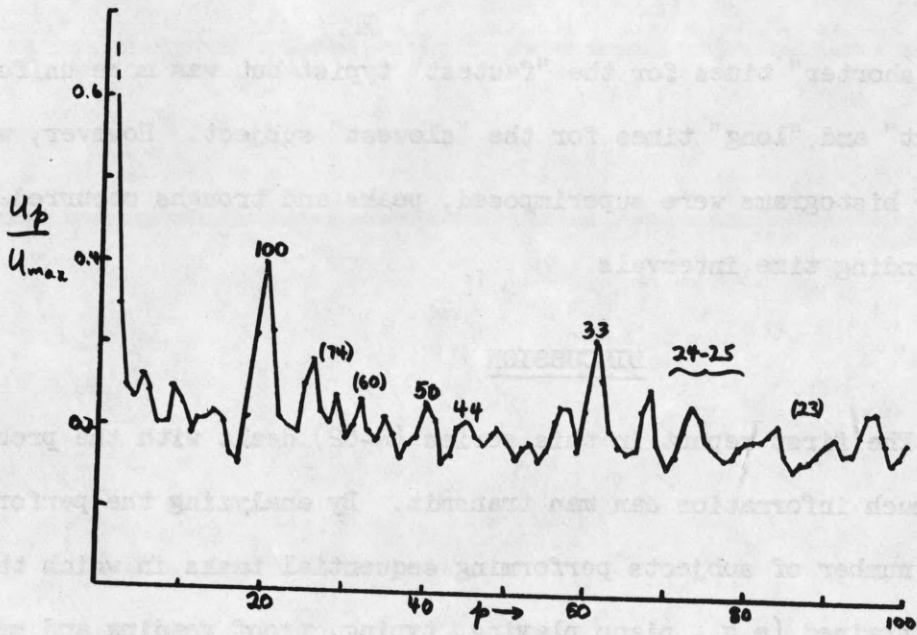
Probably the most surprising feature observed in these operations was the correlation between data from different subjects. For instance, in the typing data from experiment MRT, the distribution of the time intervals between the sequential striking of keys was skewed toward

the "shorter" times for the "fastest" typist but was more uniform over "short" and "long" times for the "slowest" subject. However, when the three histograms were superimposed, peaks and troughs occurred in corresponding time intervals.

DISCUSSION

The first report in this series (R-62) dealt with the problem of how much information can man transmit. By analyzing the performance of a number of subjects performing sequential tasks in which they were well trained (e.g., piano playing, typing, proof reading and mental arithmetic), man's transducing capacity was found to be 20-30 bits/sec. This would correspond to 20-30 binary, i.e., yes-no, decisions per second. We have attempted in subsequent studies, including the present one, to study the processes and factors which account for this overall capacity. The operating principles of a modern high-speed digital computer can be used as a convenient framework for summarizing those findings.

Data Input: A procedure quite analogous to the alternate data input and computation procedures of a computer is followed by man in reading. That is, the eye is not constantly in motion; it is relatively stationary for about 200-250 msec. in between gross, rapid movements of short duration. Flash recognition studies (R-69) indicated that data input probably occurs during only a small portion of each cycle. For instance, the amount of information which can be transmitted about complex stimuli exposed for 40 msec. is greater than that for those exposed 10 msec. However, for longer exposures no additional information is assimilated until the flash durations exceed about 250 msec. Thus, apparently there is a rapid uptake of data in about 40 msec. followed by an



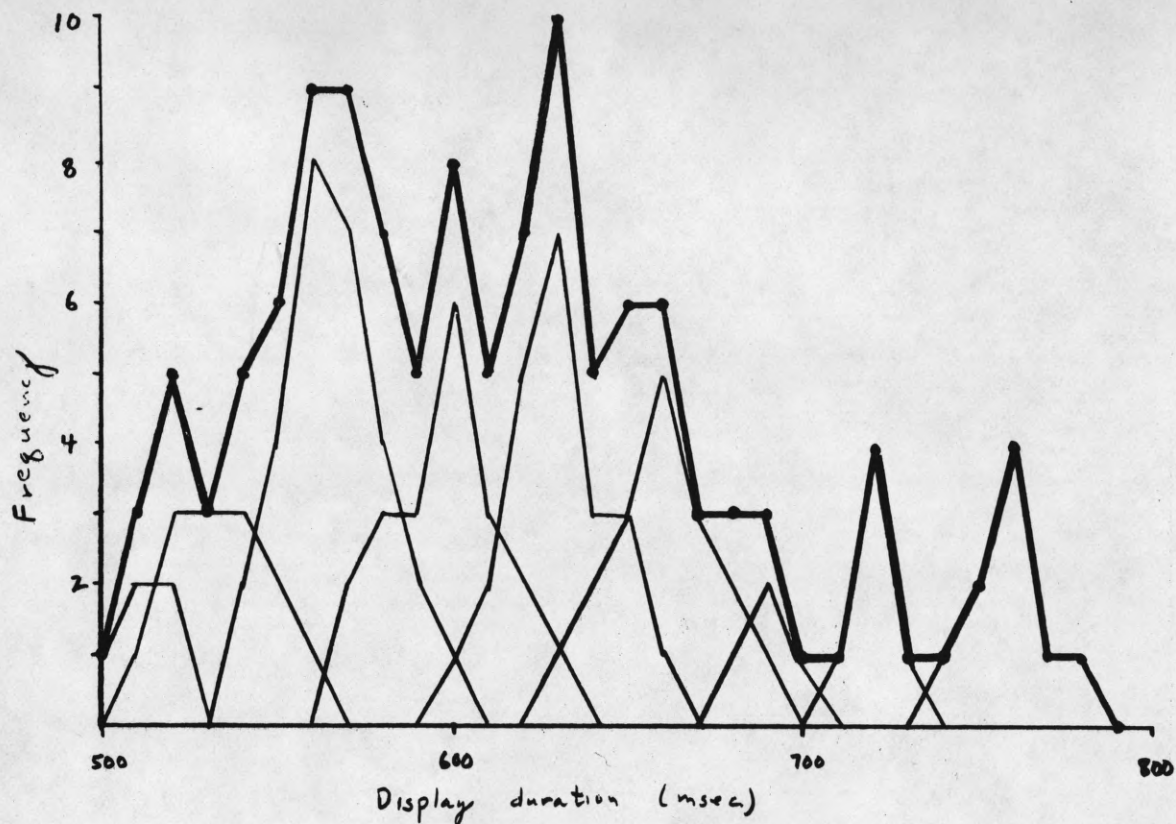


Fig. 6 The "Gaussian fitting" (see method 4, p. 75-14) of data from position 3, experiment SHN and subject B1. The heavy lines connect the observed data. The light lines are the individual "fitted" Gaussian distributions. They have the following modes and standard deviations (msec.)

mode	535	567	598	630	660	695	725	758
s. d.	16.0	16.0	16.0	15.5	16.0	-	-	13.5

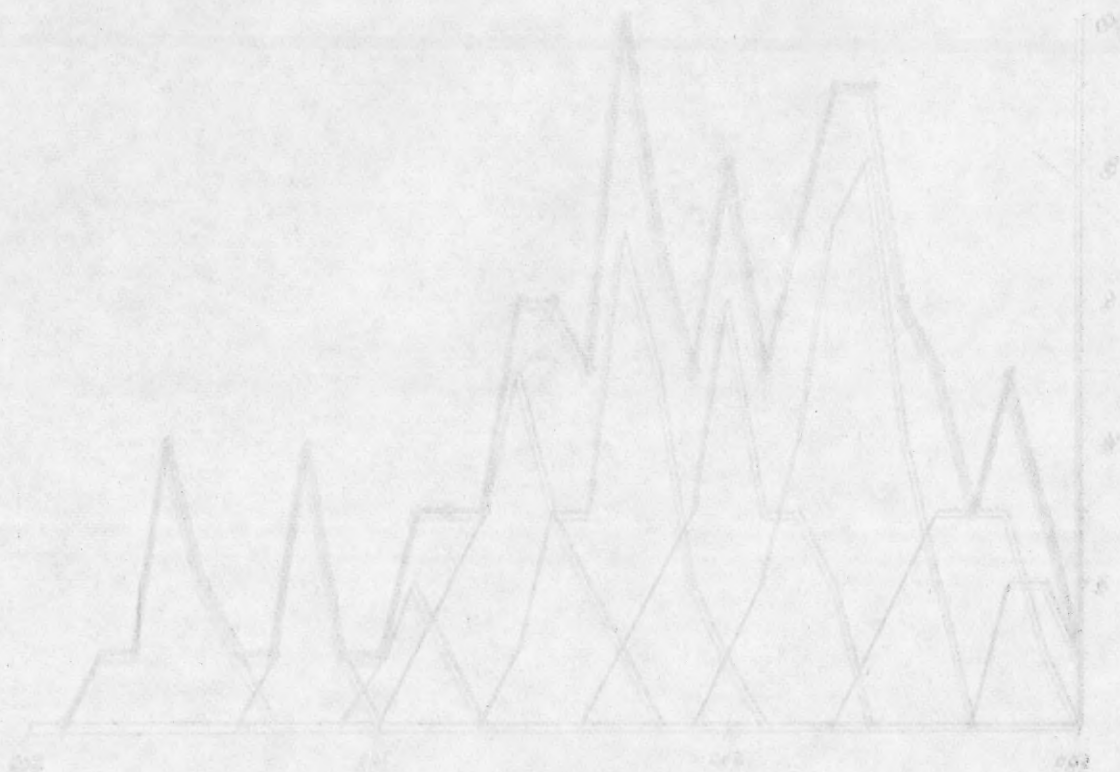


Fig. 7A Comparable "Gaussian" fitting to that in fig. 6 for data pooled for 3 subjects for the time required to type the first letter of a four letter sequence in experiment MRT.

mode	439	472	505	535	569	603
s.d.	12.5	12.5	12.7	14.0	13.0	12.0

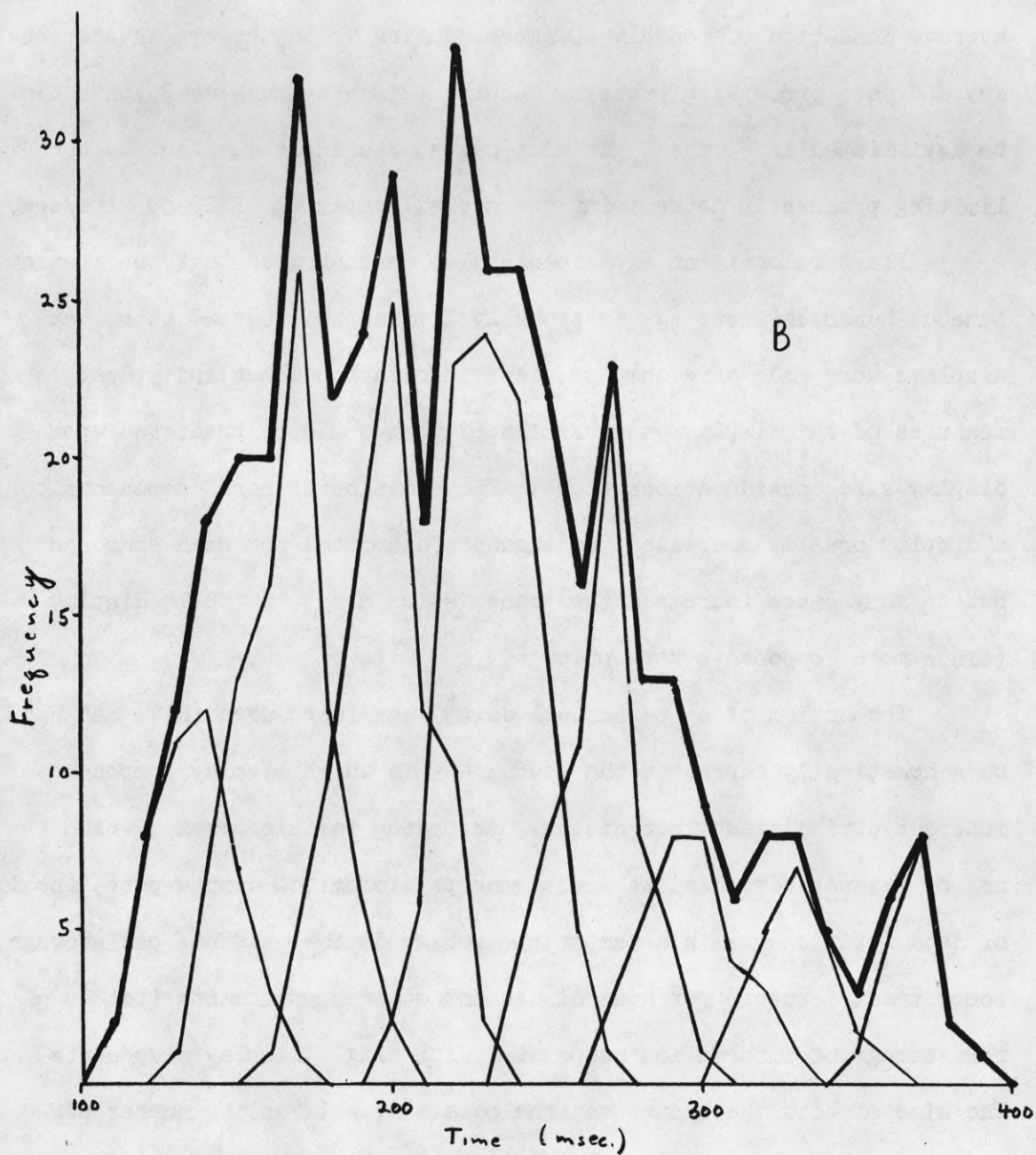


Fig. 7B Comparable "Gaussian fitting" for data pooled from 3 subjects for the interpulse time for the second, third or fourth letter of a four letter sequence in experiment MRT.

mode	136	168	199	233	266	299	332	369
s.d.	14.0	14.0	14.0	14.0	14.0	14.0	14.3	11.8

average dead-time of roughly 200 msec. during which the eye is stationary and data processing probably occurs. Since as much as 20 bits can be assimilated in 40 msec., in most cases data input must not be the limiting process in determining the overall capacity of 20-30 bits/sec.

Flash recognition experiments also demonstrated that the instantaneous human data storage is probably limited to about 20 bits. As displays were made more complex, less information about individual features of the display was assimilated than would be predicted upon display-size considerations alone. The addition of more components to a display usually decreased the amount transmitted for each component but in many cases increased the transmission about the whole display (since more components were present).

The notion of a "perceptual daisy" was introduced (R-71 and R-69) to schematically represent the lawful way in which display components interact during flash recognition. According to this scheme, which may or may not have been an exact neurophysiological counterpart, the limit of data input occurs in a temporary storage device. It has one storage compartment (center) for general use and other compartments (petals) for storage of information associated with single display components. The size of both the center and the petals as well as the number of petals varies only to a limited extent for different kinds of displays. The general scheme seems applicable to flash recognition of letters, playing cards, strips and dials.

If some variables in a display were made redundant (for example, playing cards of a single suit were used to make up a display), even though transmission was much less than perfect the subjects could not filter out the unneeded information and therefore did not improve their performance for the unaffected variables over their performance in the

non-redundant displays. This does not mean that no filtering was possible, but rather that it did not operate at the level of the data input process. Nor is the possibility excluded that there is a re-coding from the variables used in forming the stimuli to those used by the subject to represent the data in his storage mechanism; in computers there is a transformation to the binary system.

Behavior pattern or "sub-routine" selection: The human-computer analogy in this area is reasonably exact if we assume the formation of a simple habit, such as the recognition of a letter or numeral, compares to the generation and storage in the memory of a specific sub-routine (i.e., a specific set of computational procedures) whereas the formation of a complex habit is the generation and storage of a number of sub-routines plus a unique master routine. For example, when a subject is first learning a habit, his performance is usually slow and irregular; however, after many repetitions the operation becomes routinized so that his performance becomes stable and requires a minimum time for completion. This probably corresponds to the establishment of the necessary sub-routine (or modus operandi) in its final form. However, if the subject is not required to perform this particular task for a considerable length of time, the next time he is confronted with its unique stimulus his completion time will be considerably longer than it would be if he were expecting the stimulus. This may well represent the difference between the proper sub-routines being in the temporary memory initially and with the situation in which the proper sub-routine must be selected from the permanent memory and transferred into the working memory.

When humans are confronted with a completely new stress situation, which requires an almost instantaneous response, they will many times

informational demands are reduced--for instance, by rehearsing the performance. No efforts were made to experimentally determine the process by which outputs were generated nor was an attempt made to separate t_s and t_r described in eq. 2. Rather, it was possible to estimate that in our experiments $t_s + t_r \approx 200-300$ msec. and further, Δ_{sr} --which includes the variance due to factors other than inputting and processing--can be treated as a Gaussian distribution with $\sigma_{sr} \approx 13$ msec.

Data Processing: The processes of data input, selection of a modus operandi and the generation of a response have been pretty well eliminated as the rate limiting processes in the tasks studied. In those types of activities one would expect that whatever data processing is necessary for the translation of an input into an output would probably exert the greatest control on overall capacity.

The data presented in this last report of the series show strong evidences of a 100 msec. periodicity in most of our subjects. Further, many subjects showed a periodicity of about 33 msec. Thus it is concluded: 1) that the fundamental 33 msec. periods probably occur in groups of three, and so produce the strong evidence of the most prevalent 100 msec. period; 2) the 33 msec. value is probably that for both t_i and t_p ; and 3) σ_p and σ_i are about 2-4 msec.

There is an appealing correspondence between a duration of 33 msec. for the fundamental time quantum and two other parameters already cited. They are, i) a transmission capacity of 20-30 bits/second and ii) data are apparently input for only about 40 msec. every 200-250 msec. This correspondence leads to the final and fourth conclusion: Within each fundamental quantum either data are input or one binary decision can be made. This means that of the 30 unit acts per second,

most (probably 25) would be utilized for making binary decisions and the rest (about 4 or 5) for the input of data.

It is of particular interest that the 33 msec. quantum seems to be independent of the wide variety of tasks studied. This is in contrast to most computers where the duration of t_p would be a function of the complexity of the operation. Thus even the most complicated decision of which man is capable may well be the summation of a large number of binary decisions, each one performed during a unit processing act.

Although individual portions of data are probably input during a single unit act, the gross movements of the eye appear to operate on a longer duration time schedule. Data from those tasks involving vertical scanning and from experiment SLP indicate that the most likely fixation time is about 200-250 msec. In experiment SLP the minimum duration of eye fixation observed (out of approximately 500 measured fixations of 10 subjects) was 60 msec. The most likely fixation time was 230 msec. which corresponds to 6 or 7 of the fundamental quanta. Other likely fixation times were multiples of a 100 msec. longer. Those results suggest that eye movements may well be triggered by some phase of the processing cycle and the gross movement is most likely to be triggered after 6 or 8 processing quanta have elapsed.

In light of the fourth conclusion above, the estimates of 61-72 msec. as the average time devoted in SHN to processing each letter (p.75-15) are of interest. If it were necessary to specifically identify each letter before deciding it was not a number, at least 3 unit acts would be required. Yet apparently only two were involved on average. This suggests that either our subjects utilized some "short

cut" strategy or else the identification and rejection as a non-number required only 2 bits per symbol.

In this series of experiments the parameters we have measured are those which are important from an engineering standpoint. It should now be interesting and important for fundamental psychologists to deal with the problem of what neurological processes, if any, are associated with such features as the fundamental quantum or the perceptual daisy. With the parameters we have measured, it should be possible for a systems engineer to estimate how successful the component labeled MAN will be in performing the functions allotted to it in a particular data-processing system. A not too unreasonable model to assume is that man is a versatile, tolerant, and somewhat sloppy, slow-speed, quantized computer operating on a binary basis.

REFERENCES

1. Stroud, J. M., "The Moment Function Hypothesis", M. A. Thesis, Stanford University (1948).
2. Stroud, J. M., "The Fine Structure of Psychological Time", Information Theory in Psychology, Free Press, Glencoe, Illinois, ed. H. Quastler, p. 174-205 (1955).
3. Augenstine, L. G., "Evidences of Periodicities in Human Task Performance", *ibid*, p. 208-226 (1955).
4. Buswell, G., How People Look at Pictures, University of Chicago Press (1955).
5. Wallis and Moore, J. Am. Statist. Assoc. 36, 401-408 (1941).
6. Seiwel, H. R., "A New Mechanical Autocorrelator", Rev. of Sci. Instruments 21, 481-484 (1950).
7. Tukey, J. W., "The Sampling Theory of Power Spectrum Estimates", Symposium of Applications of Autocorrelation Analysis to Physical Problems, Woods Hole, Mass., 13-14 June 1949. ONR Publication NAVEXOS-P-735.