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A PERFORMANCE BASED EVALUATION OF KEYING LOGICS FOR ALPHANUMERIC KEYBOARDS

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Four keying Logics for the entry of alphanumeric characters were evaluated. The Logics were selected based on their compatability with current keyboard designs being used for the pilot-aircraft interface involving communications, navigation and other aircraft subsystems. Each of four groups of seven subjects learned one of the Logics and their performance was recorded on an alphanumeric keying task. Performance measures were keying speed and keying accuracy for alphabetic characters, numeric characters, character strings, and total list.

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Block 20 ABSTRACT

A keying Logic utilizing individual keys (36) for each alphabetic and numeric character was significantly superior to other Logics which used push-button telephone type keyboards, with regard to keying time. With regard to keying accuracy, all Logics performed equally well, with an error rate of approximately 0.5 percent. Significant performance differences among the three matrix keyboard Logics were inconsistent. Of these, one utilizing the telephone arrangement was most accurate.

Research is recommended to further examine keying performance in the learned state, as well as under more realistic conditions.

AFWAL-TR-81-3104

FOREWORD

This report documents research performed by the author while in a Long-Term Full-Time Training agreement with the Air Force Systems Command. The objective of this effort was to evaluate alternative keying logics for the entry of alphanumeric data intc aircraft subsystems.

The work was performed in support of Project 2403 "Flight Control Technology", Task 04, "Control/Display for Air Force Aircraft and Aerospace Vehicles", under Work Unit 24030411 "Workload Problem Assessment" of the USAF Wright Aeronautical Laboratories, Flight Dynamics Laboratory. Mr. Larry Butterbaugh of the Crew Systems Development Branch, Flight Control Division, was the principal investigator as well as author.

This report documents work performed during the period from April 1980 to April 1981.

Special thanks is extended to Mr. John Kozina and Mr. David Mott, both employed by the Bunker Ramo Corp., for their hard work in fabricating the keyboards and microcomputer, as well as developing the Logic programs.

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GLOSSARY

AACC	Alphabetic Accuracy - mean keying accuracy for alphabetic characters.
ASTIME	Alphabetic Stroke Time - mean stroke time for correctly keyed alphabetic characters.
ATIME	Alphabetic Time - mean keying time for correctly keyed alphabetic characters (1,2, or 3 strokes).
CLTIME	Calculated List Time - mean calculated list time for correctly keyed alphabetic and numeric characters.
LACC	List Accuracy - mean list keying accuracy.
LTIME	List Time - mean list keying time.
NACC	Numeric Accuracy - mean keying accuracy for numeric characters.
NTIME	Numeric Time - mean keying time for numeric characters.
TRANACC	Transition Accuracy - mean keying accuracy for alphabetic to numeric transitions.

SECTION I

INTRODUCTION

1. BACKGROUND

Numeric keyboards have been utilized for many years in some aircraft, such as the C-5A and F-111D; however, these keyboards are typically part of a specific aircraft subsystem (e.g., navigation system) and therefore limited, in use, to that subsystem. The current technology trend of using digital electronics in the design of airborne avionics, however, has not only created the potential for an entirely new look in aircraft crew station design (Figure 1), but also established the capability for integrated control of multiple subsystems through the use of a single integrated alphanumeric keyboard. Such a keyboard can have both advantages and disadvantages. A single, alphanumeric keyboard could serve the purpose of several currently used control heads, and thus reduce the space requirements needed for installing the standard complement of navigation and communication control boxes, for instance. Also, cost savings could be realized through the reduction of hardware components and installation time associated with dedicated subsystem controls. On the other hand, such a keyboard will significantly impact crew procedures, and require utilization by the flight crew throughout the flight. Table 1 scopes potential subsystems that could be interfaced with an alphanumeric keyboard, and the flight segments during which the keyboard could find use.

In response to the potential advantages, subsystems are appearing on the market which have incorporated a full alphanumeric keyboard (Figures 2, 3, 4). Such subsystems, at present, are primarily integrated navigation systems which require the input of the alphabetic navigation aid identifiers (i.e., air route intersections) in addition to the numeric input of latitudes and longitudes.

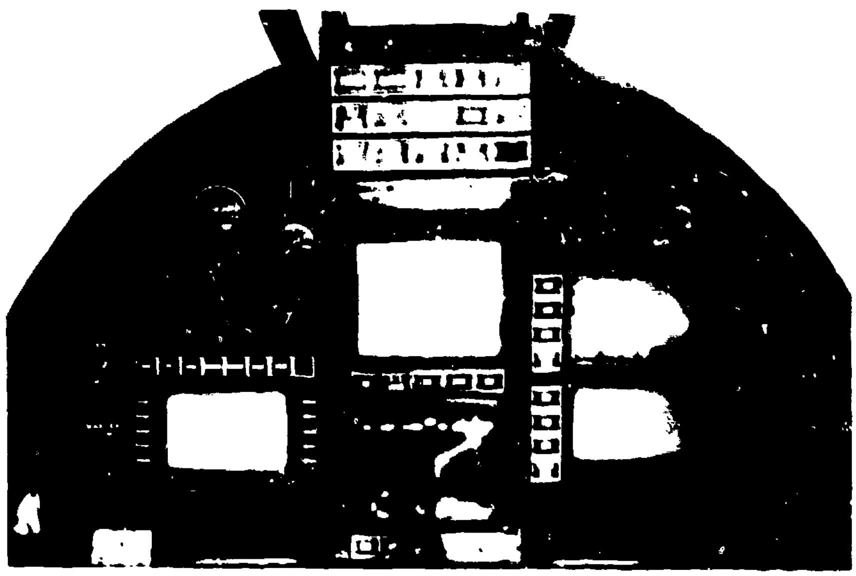


Figure 1. Advanced Avionics Aircraft Crew-tation.

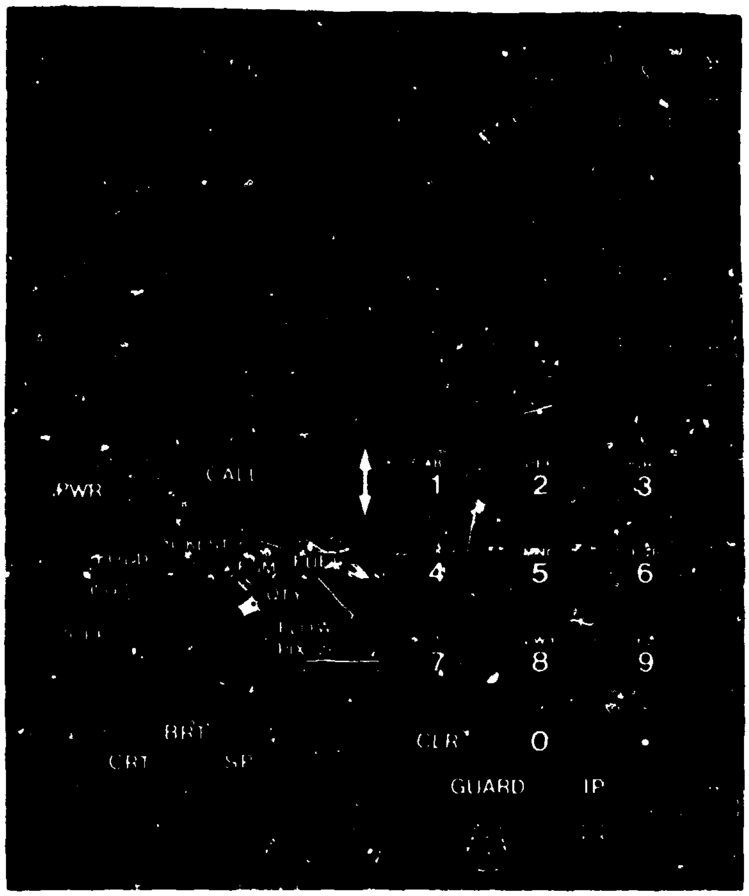


Figure 2. Integrated Avionics Control System (Collins Radio Co.)

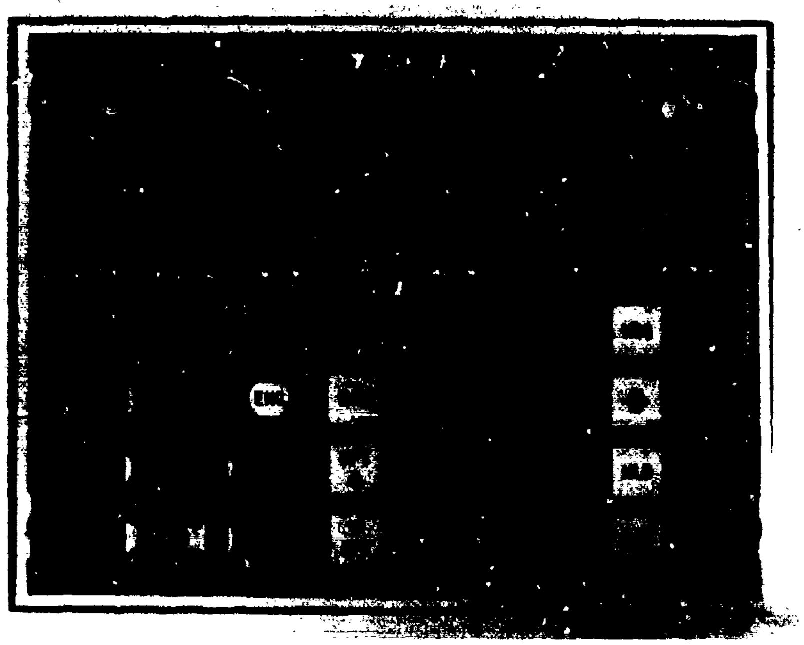


Figure 3. Automatic Navigation System (Sperry Corp.)

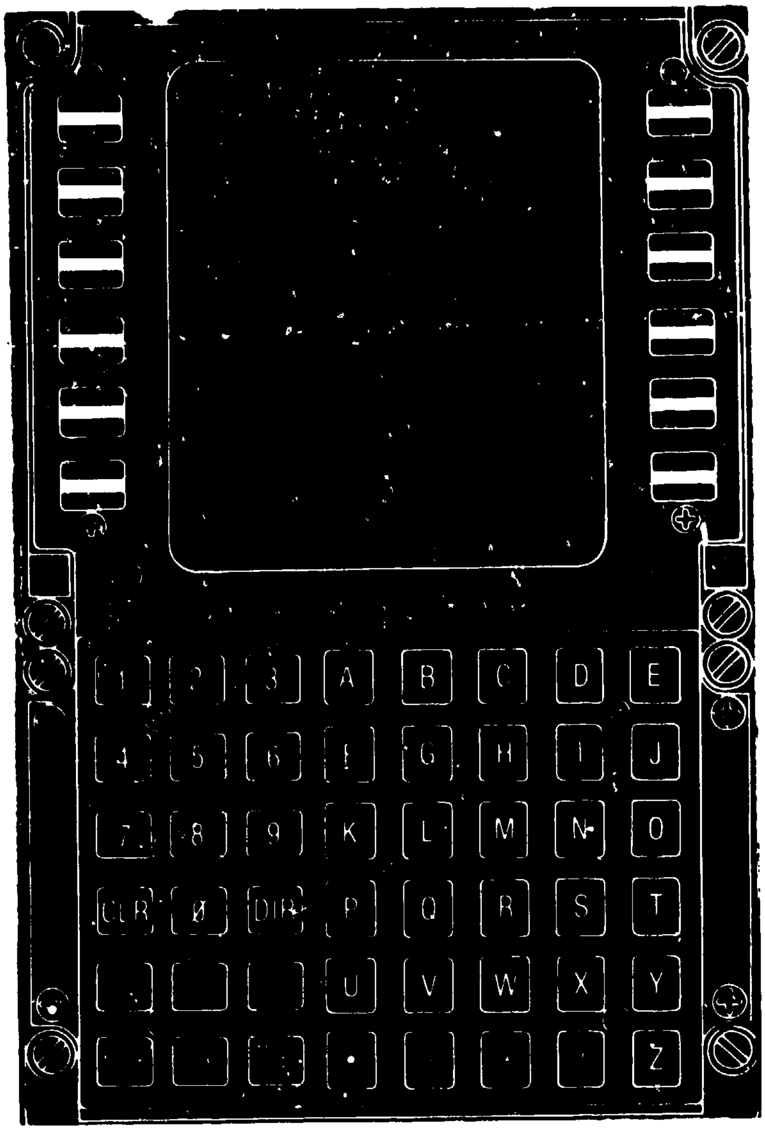


Figure 4. Automatic Navigation Control/Display Unit (Collins Radio Co.)

TABLE 1

POTENTIAL KEYBOARD APPLICATIONS

FLIGHT SEGMENT	Nav	Comm	Cklst	Weapons	Flight Control	Sensors
Preflight	X	X	X	X	X	X
Taxi		X	X		X	
Takeoff/Climb	X	X	X		X	X
Cruise	X	X	X	X	X	X
Descent/Landing	X	X	X		X	X
Weapon Delivery		X		X		X

An alphanumeric keyboard for these systems could be implemented in the form of the "QWERTY" (typewriter) design, if there weren't space and operational constraints applicable to keyboard implementation in aircraft.

Space limitations in aircraft crew stations have been a continual constraint on designers. The impact of this constraint on keyboard design is that all 36 alphanumeric characters (26 alphabetic + 10 numeric) usually do not have a dedicated key for their input. As a result, multifunction keys are being utilized in keyboard designs, producing keyboards with 12 keys in a 4 x 3 matrix (Figures 5, 6).

The operational constraint applicable to keyboard design and implementation is that it be operable with one hand, while wearing gloves, and based on the desirability to locate the keyboard between the pilot and copilot, it must be operable by either hand. These space and operation constraints make it apparent that the conventional alphanumeric keyboard (QWERTY) is not feasible and further research should be directed toward the implementation of another type of keyboard.

Several U.S. Government data bases were searched including the Defense Technical Information Center (formerly the Defense Documentation Center) and the Control/Display Information Center, in order to locate any relevant keyboard research funded by the Department of Defense, the Federal Aviation Administration, the National Aeronautics and Space Administration, or other U.S. Government agencies. Also, the DIALOG data base was searched for relevant research reported in technical journals or in conference proceedings.

These data searches revealed that up to now, the evaluation of such systems in the context of subsystem operation has been restricted to the entry of numeric characters. Bateman, et. al. (1978) (Reference 1) and Reising, et. al. (1977) (Reference 2) evaluated a system

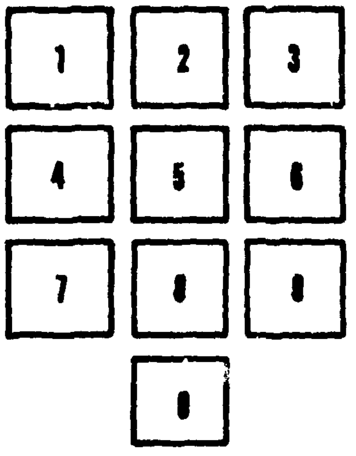


Figure 5. 4 x 3 Matrix Keyboard; Top-to-Bottom (Telephone) Arrangement

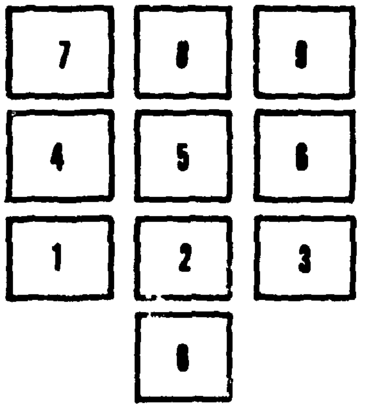


Figure 6. 4 x 3 Matrix Keyboard; Bottom-to-Top (Calculator) Arrangement

incorporating a numeric keyboard (telephone configuration) but did not report performance related to the keyboard. Deininger (1960) (Reference 3) studied 16 numeric key arrangements and found small differences, in keying speed, between the now standard telephone arrangement and the calculator arrangement (.70 second/character for the telephone vs. .73 second/character for the calculator). This same study failed to find a difference in error rates, also. Lutz and Chapanis (Reference 4) evaluated the telephone arrangement against the calculator arrangement and reported that telephone arrangment is "expected" on a numeric keyboard with a frequency of 5 to 1. Alden, et. al. (1972) (Reference 5) reviewed the design issues surrounding alphanumeric keyboards (e.g., key displacement, force, etc.) as well as the results of various studies investigating key arrangements. Of these, one study by Paul, et. al. (1965) (Reference 6) evaluated the telephone alphanumeric arrangement against the calculator arrangement and found the telephone arrangement superior both for alphanumerics and alphabetics alone, and no difference in numeric keying. Conrad (1967) (Reference 7) and Conrad and Hull (1968) (Reference 8) evaluated the telephone arrangement against the calculator arrangement, and found the telephone arrangement to have superior speed (.67 second/character vs. .73 second/character) and accuracy (.55% errors vs. 1.16% errors). Klemmer and Lockhead (1962) (Reference 9) studied average error rates for keypunch installations (calculator arrangement) and found values ranging between .2% and .06%.

In related research, Devoe (Reference 10) (1967) evaluated alphanumeric keying time against alternative methods of data entry and found the keying of formatted data to be faster than all but printing. Also, Neal (1977) (Reference 11) studied the time interval between key strokes, which was found to be on the order of .15 second. Also studied by Neal was the time to key strings of characters using two-handed keyboards, which was found to average about .25 second/character. Dean (1969) (Reference 12) evaluated the effects of vibration on data entry performance, and found that vibration appeared to have no effect on accuracy but did increase keying time by as much as .25 second/character.

Other types of keying have also been studied. Ratz and Richie (1961) (Reference 13) and Seibel (1962) (Reference 14) studied one-handed chording keyboards but reported single-finger key presses as the fastest.

While much research has been directed toward the arrangement of keyboards, and keying versus alternative inputting methods, research regarding the logic associated with keyboards is lacking, or at least not reported. This is very disconcerting in light of the marketed designs and their obvious differences regarding keying logic.

This research, therefore, is an initial investigation regarding the various logics which can be employed to key-in alphanumeric characters. Optimally, all associated issues regarding keying performance, such as the effect of flight clothing (i.e., gloves) and the effect of the logics on a simultaneous tracking task will have to be addressed. However, this research focuses on the study of the logics themselves. Therefore, a relatively pure experimental context was designed in order to study the performance differences contributed by the logics.

2. RESEARCH QUESTION

The objective of this research was to evaluate alternative keying logics. Specifically, three logics compatible with the 4 x 3 matrix keyboard and a logic utilizing an 8 x 6 matrix of single-function keys were examined with regard to their effects on keying performance.

Aside from noting any performance differences, it was also the intent of this research to isolate why there are differences between logics. This was accomplished by examining the results for any relation to logic structure, procedure, etc.

3. SIGNIFICANCE

The results of this study should find useful application in the design of advanced aircraft subsystem controls which very likely will utilize alphanumeric keyboards for data entry into navigation, communication, and other subsystems. While investigated in the context of a navigation data entry task for aircraft applications, the results are applicable to similar tasks in other contexts requiring one-hand alphanumeric keying.

4. ORGANIZATION OF REPORT

Having established a void between human performance data and keyboard design trends, this report proceeds with a description of the detail of the experimental procedure (Section II), the statistical results associated with the collected data (Section III), a discussion of the factors associated with these results (Section IV), and concludes with a design recommendation and further research recommendations (Section V).

SECTION II

EXPERIMENTAL PROCEDURE

1. KEYBOARD LAYOUTS

Three alphanumeric keyboard designs were used to evaluate four logics for keying alphabetic and numeric characters. Two designs utilized a 6-key by 3-key matrix arrangement similar to that found on push button telephones. The third design utilized a 6-key by 8-key matrix arrangement. Each keyboard provided the full complement of 26 alphabetic and ten numeric characters, as well as six special function capabilities. The special functions incorporated into these keyboards were similar to those found on commercially available navigation management systems, and included a forward space, a backward space, a clear entry, an enter, a slash (/), and an alphabet mode key. The three keyboard designs are shown in Figures 7, 8, and 9. For purposes of standardizing the references to these designs throughout this report, these designs will be referred to as Keyboard A, Keyboard B, and Keyboard C, respectively.

Keyboard A (Figure 7) has the standard top-to-bottom numeric arrangement, which has been found superior in previous studies Alden, (Reference 5), and an alphabetic arrangement that has been proposed within the United States Air Force Aeronautical Systems Division for incorporation into a standardized avionics integrated control system (Reference 15).

Keyboard B (Figure 8) incorporates an arrangement which was developed as an efficient computer interface, while retaining the original function of the push button telephone (Reference 16). This design has as its foundation the frequency distribution of English letters and minimizes the occurrence of the most frequent letters (i.e., e, t, a, o, i, n, s, h, r, d, . . .) in the middle position

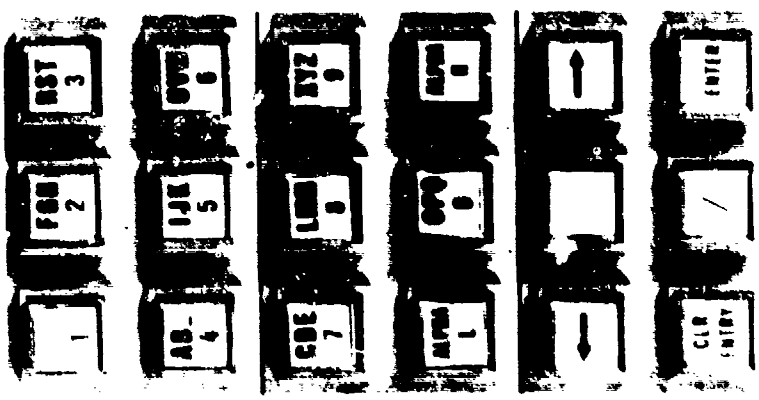


Figure 8. Keyboard B

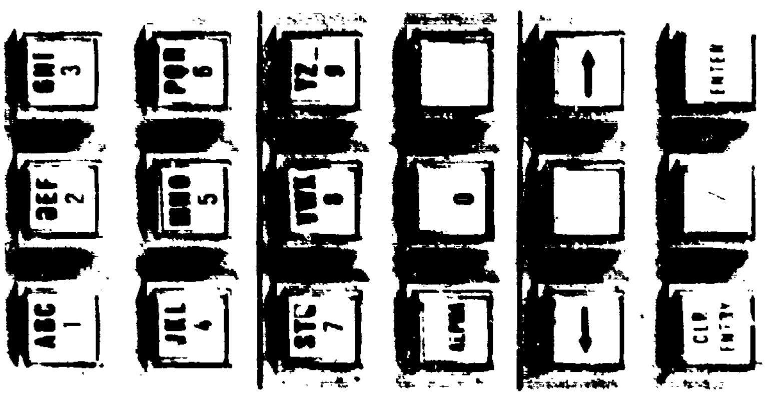


Figure 7. Keyboard A

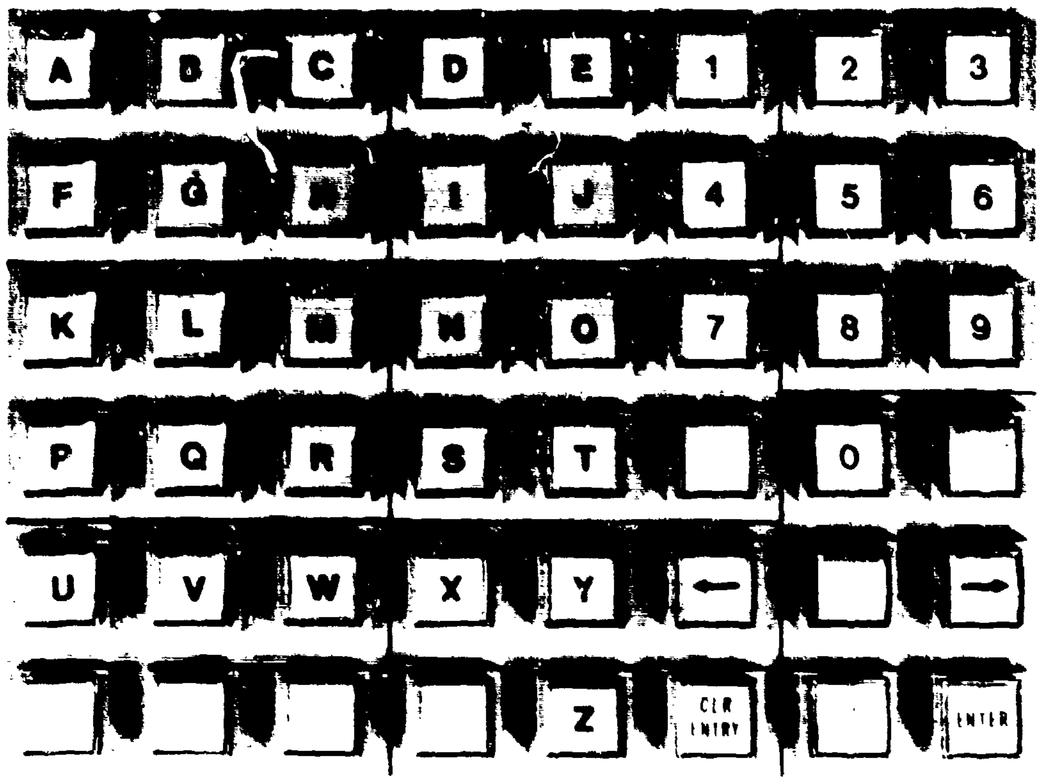


Figure 9. Keyboard C

on a key. (The concern for their location is based on the need of an additional key-press, in order to specify a letter in the middle position, over the two key-presses necessary to specify a letter in either the left or right position. Refer to the discussion of Logic 3 in this section for further details regarding the keying logic associated with this design).

Keyboard C (Figure 9) is a design functionally separating the alphabetic and numeric keys. This layout incorporates individual keys for each character, which is representative of commercially available designs, and is intended for one-handed operation.

For purposes of the study reported herein, the special functions provided on the keyboards were standardized with regards to operation and location.

2. KEYING LOGICS

Four alphabetic character keying logics (two associated with Keyboard A, one associated with Keyboard B, and one associated with Keyboard C) were identified and evaluated. The logic associated with keying a numeric character was the same for all keyboards and will, therefore, be described first.

a. Numeric Character Keying

Numeric character keying was accomplished by selecting the appropriately labeled key on the keyboard, and depressing. Repeated keying of a particular number, or keying of a sequence of numbers required a key depression for each character.

b. Alphabetic Character Keying

Alphabetic character keying was accomplished by one of four logics. Each logic was specific to a keyboard design for the purposes of this research. Logic 1 and Logic 2 were studied using Keyboard A. Logic 3 was studied using Keyboard B. Logic 4 was studied using Keyboard C.

(1) Logic 1

Alphabetic characters were obtained using this logic by depressing, in sequence, three appropriate keys. The first key in the sequence is always the 'alpha' key (this is the [ALPHA] key in Figure 7). The second and third key depressions specify the desired letter. The second key depressed is the key which has the desired letter in its alphabetic subset (e.g., the '1' key in Figure 7 has on it the alphabetic subset of 'A, B, and C'). The third key depressed, and the one which specifies the individual letter desired, is the key within the same row of the 6-key by 3-key matrix as the second key, which corresponds to the left, middle, or right position of the desired letter within its alphabetic subset. Illustrating Logic 1 (Figure 7), creating the alphanumeric string '123BRAV0456' would consist of the following sequence of key depressions:

[ABC 1]	generates the number '1'
[DEF 2]	generates the number '2'
[GHI 3]	generates the number '3'
[ALPHA]	initiates alphabetic mode
[ABC 1]	identifies alphabetic subset (A, B, C)
[DEF 2]	specifies 'B'
[ALPHA]	initiates alphabetic mode
[PQR 6]	identifies alphabetic subset (P, Q, R)
[PQR 6]	specifies 'R'

ALPHA	initiates alphabetic mode
ABC 1	identifies alphabetic subset (A, B, C)
ABC 1	specifies 'A'
ALPHA	initiates alphabetic mode
VWX 8	identifies alphabetic subset (V, W, X)
STU 7	specifies 'V'
ALPHA	initiates alphabetic mode
MNO 5	identifies alphabetic subset (M, N, O)
PQR 6	specifies 'O'
JKL 4	generates the number '4'
MNO 5	generates the number '5'
PQR 6	generates the number '6'

(2) Logic 2

As in Logic 1, alphabetic characters are obtained by depressing in sequence, three appropriate keys. The first key in the sequence, as it is in Logic 1, is always the 'alpha' key. The second key in the sequence, is, again, the key which has the desired letter in its alphabetic subset. The third key depressed for Logic

2, however, is always the '1', '2', or '3' key, depending on whether the desired letter is in the left, middle, or right position of the alphabetic subset identified by the second key depression.

Illustrating Logic 2 (refer to Figure 7), the alphanumeric string '123BRAV0456' is created by the following sequence of key depressions:

ABC 1	generates the number '1'
DEF 2	generates the number '2'
GHI 3	generates the number '3'
ALPHA	initiates the alphabetic mode
ABC 1	identifies alphabetic subset (A, B, C)
DEF 2	specifies 'B'
ALPHA	iniitates alphabetic mode
PQR 6	identifies alphabetic subset (P, Q, R)
GHI 3	specifies 'R'
ALPHA	initiates alphabetic mode
ABC 1	identifies alphabetic subset (A, B, C)
ABC 1	specifies 'A'
ALPHA	initiates alphabetic mode

VWX 8	identifies alphabetic subset (V, W, X)
ABC 1	specifies 'V'
ALPHA	initiates alphabetic mode
MNO 5	identifies alphabetic subset (M, N, O)
GHI 3	specifies 'O'
JKL 4	generates the number '4'
MNO 5	generates the number '5'
PQR 6	generates the number '6'

(3) Logic 3

Alphabetic characters are obtained using this logic by depressing, in sequence, either two or three keys, depending on the position of the desired letter within an alphabetic subset. This logic has two 'alpha' keys as shown in Figure 8. Letters in the left or right position within an alphabetic subset require two sequential key depressions. The first key depression is either the 'ALPHA L' or 'ALPHA R', depending on whether the desired letter is in the left or right position within the alphabetic subset, respectively. The second key depressed in the sequence of two is the key that has the desired letter. The middle letter in an alphabetic subset requires three key depressions, in sequence, in order to be selected. The first and second key depressed is always the 'ALPHA L' and 'ALPHA R', respectively. The third key depressed in this sequence is the key that has the desired letter in its alphabetic subset.

Illustrating Logic 3 (refer to Figure 8), the alphanumeric string '123BRAV0456' is created by the following sequence of key depressions:

[1]	generates the number '1'
[FGH 2]	generates the number '2'
[RST 3]	generates the number '3'
[ALPHA L]	initiates alphabetic mode
[ALPHA R]	specifies middle letter of alphabetic subset
[AB_ 4]	identifies alphabetic subset (A, B, C), generates 'B'
[ALPHA L]	initiates alphabetic mode, specifies left letter of alphabetic subset
[RST 3]	identifies alphabetic subset (R, S, T), generates 'R'
[ALPHA L]	initiates alphabetic mode, specifies left letter of alphabetic subset
[AB_ 4]	identifies alphabetic subset (A, B, _), generates 'A'
[ALPHA L]	initiates alphabetic mode
[ALPHA R]	specifies middle letter of alphabetic subset
[UVW 6]	identifies alphabetic subset (U, V, W), generates 'V'
[ALPHA L]	initiates alphabetic mode, specifies left letter of alphabetic subset
[OPQ 0]	identifies alphabetic subset (O, P, Q), generates 'O'

[AB_ 4] generates the number '4'

[[illegible] 5] generates the number '5'

[UVW 6.] generates the number '6'

(4) Logic 4

Alphabetic characters are created with this logic by depressing the key corresponding to the desired letter. Illustrating this logic (Figure 9), the alphanumeric string '123BRAV0456' is created by depressing, in sequence, the following keys:

[1•] generates the number '1'

[2] generates the number '2'

[3] generates the number '3'

[B] generates the letter 'B'

[R] generates the letter 'R'

[A] generates the letter 'A'

[V] generates the letter 'V'

[O] generates the letter 'O'

[4] generates the number '4'

[5] generates the number '5'

[6] generates the number '6'

3. TEST HARDWARE

a. Keyboards

The three keyboards used in this research all incorporated GRAYHILL Series 82 Single-Pole, Push Button Switch Modules. These switches have a total travel of .130 inch (3.3mm), a travel to contact of .050 inch (1.3mm), and an operating force of 4.0 ounces (114.3gm). The switches were pre-assembled by GRAYHILL, Inc. into 6-key modules (2-key by 3-key) with a center-to-center distance of .687 inch (17.4mm) and a key separation distance of .279 inch (7.1mm) (Reference 17). The modules were mounted in a sheet-aluminum case which had a 15-degree upward slope, front to back. The case was painted black using Federal Standard Number 595A (Reference 18) color number 17038. The keys all had color-coded backgrounds with black characters overlayed. The 'special' function keys on all keyboards were black letters (No. 17038) (Reference 18) on a white (No. 37875) (Reference 18) background. Alphabet labels on the keyboards had a gold (Reference 18) (No. 33481) background, while the numbers had a yellow (Reference 18) (No. 33695) background.

Keyboards A and B had Franklin Gothic Extra Condensed style characters on the alphanumeric keys. Ten-point characters were used providing a character height of .1 inch (2.5mm), a stroke width to character height ratio of 1/5, and a character width to character height ratio of 1/2.

Keyboard C had Helvetica Medium style characters on the alphanumeric keys. Fourteen-point characters were used providing a character height of .125 inch (3.17mm), a stroke width to character height ratio of 1/5, and a character width to character height ratio of 1/1.25.

The characters on the 'special' function keys were the same for all keyboards. They were 8-point Franklin Gothic Extra Condensed characters with a height of .08 inch (2.03mm), a stroke width to character height ratio of 1/5, and a character width to character height ratio of 1/3.

b. Cathode Ray Tube (CRT) Display

An RCA, model TL 1209, black and white monitor was used to provide the subjects visual feedback. The display area was seven inches wide by five inches high (17.7cm by 12.7cm). The characters displayed were .25 inch high (6.35mm), had a stroke width to character height ratio of 1/8, and a character width to character height ratio of 1/1.6.

c. Microcomputer

The micro computer (Figure 10) used in this research was fabricated in the Flight Dynamics Laboratory by personnel of the Bunker Ramo Corporation. The backbone of the microcomputer was a Motorola 6808 Read Only Memory used for the video display generator executive program (formatted in Kansas City Standard) and the clock, a Motorola 6847y video display generator (Debug System; TV-Bug Version 1.2 by Motorola-Austin, Texas), 4 K of Random Access Memory (RAM) used for the keyboard logic software input, the printer output buffer, and the displayed output, and input/output ports.

The system is diagrammed in Figure 11. The keyboard logic was stored on audio cassette tape and loaded into the RAM for each system operation. Output displayed on the CRT was repeated on a Teletype model 3320 5JC printer. In addition, clock time was printed out on the Teletype printer as predetermined events involving the keyboard occurred.

4. EXPERIMENTAL DESIGN

a. Research Question

The research question being investigated is whether there is any difference among the four previously discussed keyboard logics, as measured by subject performance. In particular, it was the intent to evaluate these keyboard logics in such a manner that a single logic might be recommended for aircraft applications.

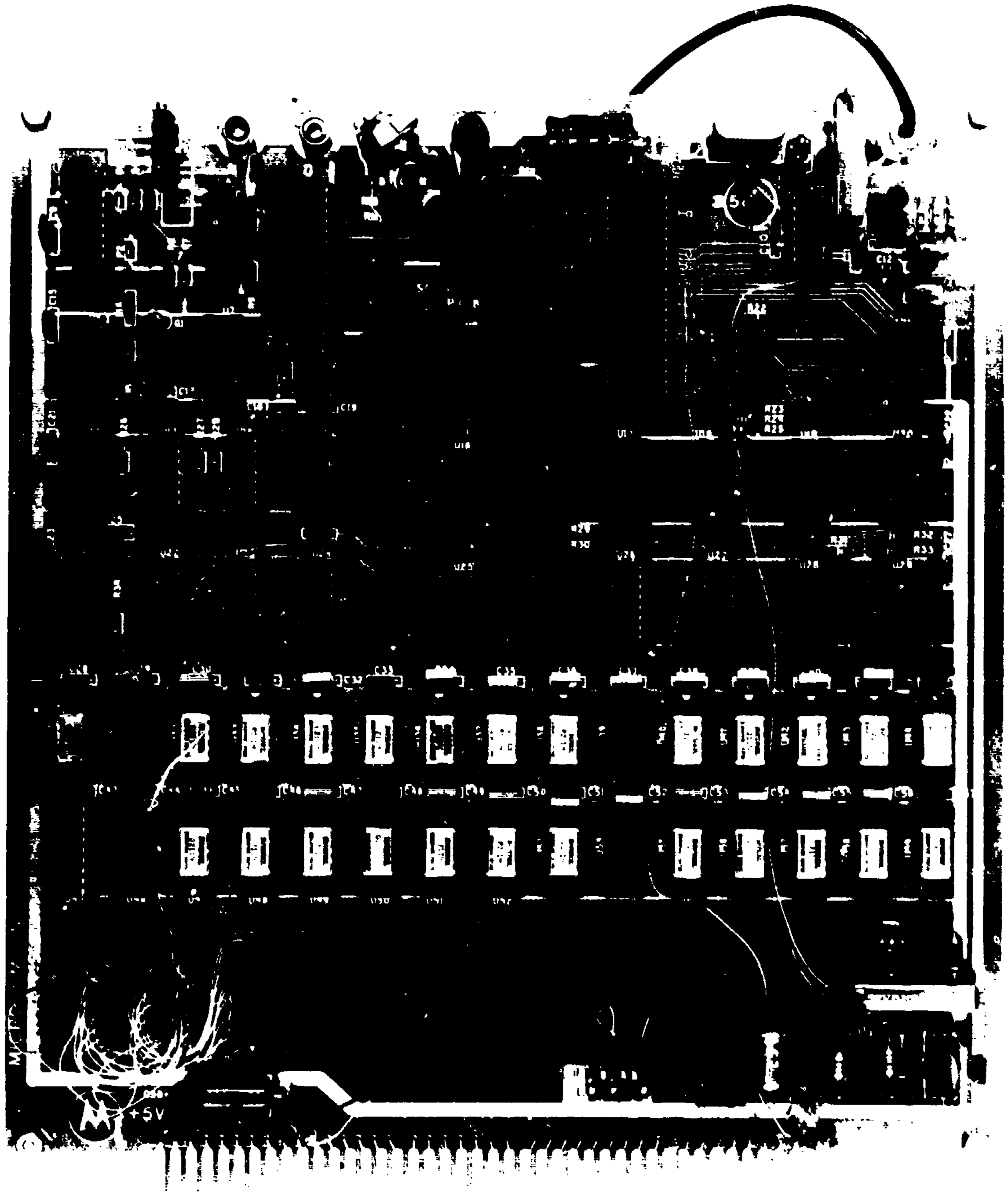


Figure 10. Microcomputer.

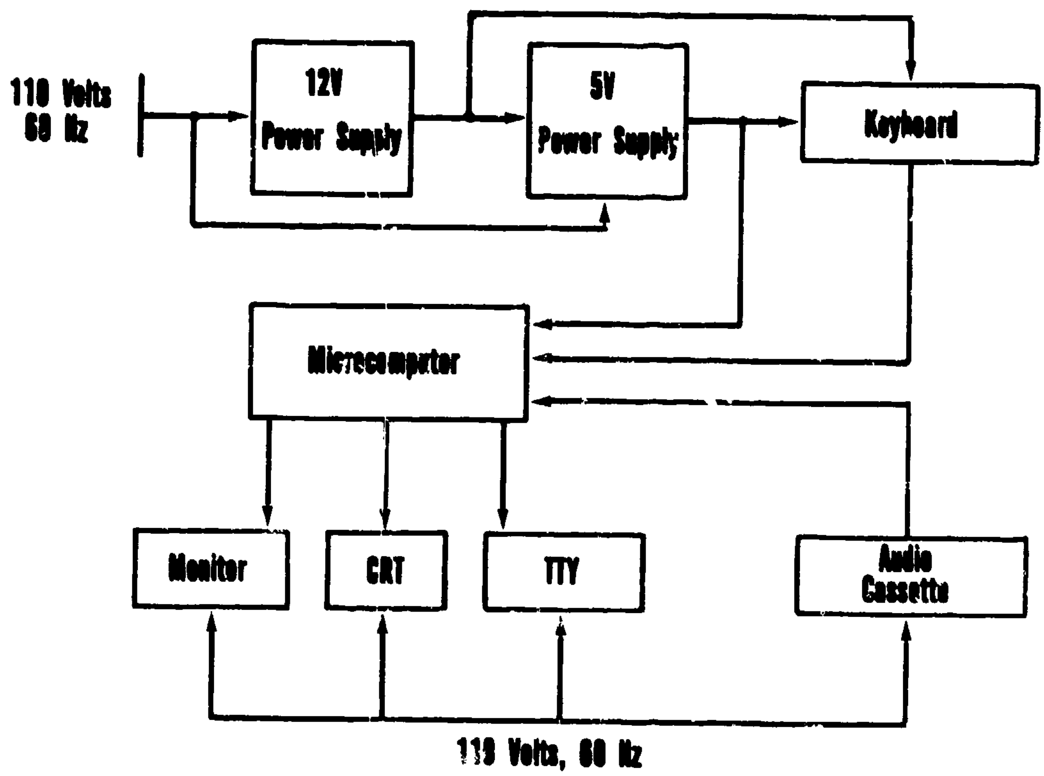


Figure 11. System Block Diagram

In order to test for the aforementioned differences, a split-plot factorial experiment was designed. In order to apply this design, the following assumptions are required (Reference 19):

- Observations are drawn from normally distributed populations
- Observations represent random samples from populations
- The population variances are equal
- The unbiased estimators of the population variance (numerator and denominator of F ratio) are independent

The layout of the design with four levels of Treatment A (Logics 1, 2, 3, and 4), three levels of Treatment B (Replications 1, 2, and 3), and seven subjects per level of Treatment A is shown in Figure 12.

b. Independent and Dependent Variables

The independent variables were the four keyboard/logic combinations and the three replications of the task.

The dependent variables consisted of keying time and keying accuracy measures.

c. Subjects

The experimental plan called for 28 subjects. Three female and 25 male scientists and engineers form the Air Force Wright Aeronautical Laboratories' Flight Dynamics Laboratory participated on a voluntary basis. Each subject was randomly assigned to one of the four levels of the keyboard/logic treatment. None of the subjects had prior experience with one-handed alphanumeric keyboards of the type studied. All subjects were between the ages of 25 and 55, and had 20/20 vision (corrected or uncorrected).

	Replication 1	Replication 2	Replication 3	
S_1	$R_{1,1}$	$R_{1,2}$	$R_{1,3}$	
S_2	$R_{2,1}$	$R_{2,2}$	$R_{2,3}$	
S_3	$R_{3,1}$	$R_{3,2}$	$R_{3,3}$	T_1 = Keyboard A Logic 1
S_4	$R_{4,1}$	$R_{4,2}$	$R_{4,3}$	
S_5	$R_{5,1}$	$R_{5,2}$	$R_{5,3}$	
S_6	$R_{6,1}$	$R_{6,2}$	$R_{6,3}$	
S_7	$R_{7,1}$	$R_{7,2}$	$R_{7,3}$	
S_8	$R_{8,1}$	$R_{8,2}$	$R_{8,3}$	
S_9	$R_{9,1}$	$R_{9,2}$	$R_{9,3}$	
S_{10}	$R_{10,1}$	$R_{10,2}$	$R_{10,3}$	
S_{11}	$R_{11,1}$	$R_{11,2}$	$R_{11,3}$	T_2 = Keyboard A Logic 2
S_{12}	$R_{12,1}$	$R_{12,2}$	$R_{12,3}$	
S_{13}	$R_{13,1}$	$R_{13,2}$	$R_{13,3}$	
S_{14}	$R_{14,1}$	$R_{14,2}$	$R_{14,3}$	
S_{15}	$R_{15,1}$	$R_{15,2}$	$R_{15,3}$	
S_{16}	$R_{16,1}$	$R_{16,2}$	$R_{16,3}$	
S_{17}	$R_{17,1}$	$R_{17,2}$	$R_{17,3}$	T_3 = Keyboard B Logic 3
S_{18}	$R_{18,1}$	$R_{18,2}$	$R_{18,3}$	
S_{19}	$R_{19,1}$	$R_{19,2}$	$R_{19,3}$	
S_{20}	$R_{20,1}$	$R_{20,2}$	$R_{20,3}$	
S_{21}	$R_{21,1}$	$R_{21,2}$	$R_{21,3}$	
S_{22}	$R_{22,1}$	$R_{22,2}$	$R_{22,3}$	
S_{23}	$R_{23,1}$	$R_{23,2}$	$R_{23,3}$	
S_{24}	$R_{24,1}$	$R_{24,2}$	$R_{24,3}$	T_4 = Keyboard C Logic 4
S_{25}	$R_{25,1}$	$R_{25,2}$	$R_{25,3}$	
S_{26}	$R_{26,1}$	$R_{26,2}$	$R_{26,3}$	
S_{27}	$R_{27,1}$	$R_{27,2}$	$R_{27,3}$	
S_{28}	$R_{28,1}$	$R_{28,2}$	$R_{28,3}$	

Figure 12. Experimental Layout

d. Analysis Strategy

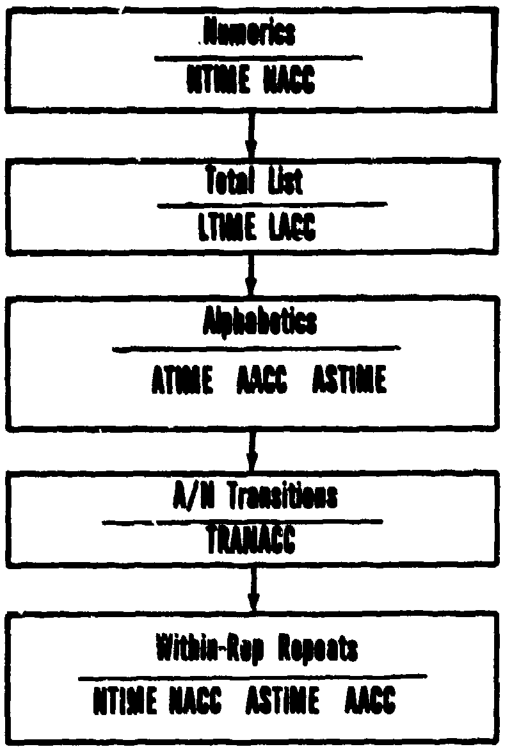
The data analysis followed the progression of Figure 13 and permitted examination of the data consistent with the following research questions:

- Is there a Logic effect on keying performance?
- Which performance measures (keying speed and/or keying accuracy) are sensitive to the Logics?
- What is the source of any Logic effect? (e.g. number of keystrokes, number of errors, etc.)

As an initial step, keying time and keying accuracy for numeric clusters (a string of consecutive numeric characters only) were analyzed. Mean numeric keying time (NTIME, the mean time to key a single numeric character) and mean numeric accuracy (NACC, the mean proportion of correctly keyed numeric characters to total numeric characters) were obtained for each replication of each logic and subsequently evaluated graphically and statistically. The numeric data were used to test the experimental assumption that the subjects used in the research were from a homogeneous (i.e., that no significant difference, either practical or statistical, existed between subject groups).

Keying performance for the total list was examined to obtain an overall perspective of any Logic or Replication (learning) effect. Mean keying time (LTIME, mean time to key the entire alphanumeric list in Figure 15) and mean keying accuracy (LACC, mean proportion of correctly keyed characters to the total number of characters) were plotted, and statistically analyzed for both Logic and Replication effects.

In order to locate any Logic or Replication effect associated with keying alphabetic characters, mean alphabetic keying time (ATIME, the mean time to key a single alphabetic character), mean alphabetic



AACC	Alphabetic Accuracy
ASTIME	Alphabetic Stroke Time
ATIME	Alphabetic Time
LACC	List Accuracy
LTIME	List Time
NACC	Numeric Accuracy
NTIME	Numeric Time

Figure 13. Analysis Strategy

stroke time (ASTIME, the mean time per stroke for keying an alphabetic character), and mean alphabetic keying accuracy (AACC, the mean proportion of correctly keyed alphabetic characters to total alphabetic characters) were obtained from alphabetic clusters (a string of consecutive alphabetic characters only) and analyzed. The ASTIME parameter was analyzed in addition to ATIME, because the different logics required a different number of key-presses, or strokes, to create an alphabetic character (refer to the Logic descriptions in Section II). Also, ASTIME is the alphabetic parameter equivalent to NTIME for numerics, since numeric characters required only one stroke in all cases (NTIME is the mean stroke time per numeric character).

In addition to the numeric and alphabetic clusters, there were clusters that contained an alphabetic character followed immediately by a numeric character (e.g., B310 D67 or FL200). While the keying time for an alphabetic/numeric transition was imbedded in the time to key in the entire cluster and unextractable, keying accuracy associated with these transitions was available. Mean transition accuracy (TRANACC, the mean proportion of correctly keyed characters in the two-character transition to the total characters in all transitions) for each Logic and Replication was obtained and statistically analyzed for any resulting effect.

In order to isolate any within-replication learning that might be occurring, the list of alphanumeric clusters used for this research contained repeats of selected clusters (e.g., ABC, JUVTY, 495). Mean values of AACC, ASTIME, NACC, and NTIME across subjects were obtained, for both the initial and repeated occurrence, for each Logic and Replication. These data were plotted and analyzed for any significant learning trend.

In addition, other analyses of the data were performed in isolated cases to answer specific performance related questions. These isolated analyses, as well as the other analyses mentioned above are discussed in more detail in Section III and Section IV.

5. PROTOCOL

Each subject participated in one session which consisted of instruction, practice, and data collection. The subjects performed the keyboard task seated at a table. The CRT was directly in front of the subject and slightly below the horizontal line-of sight. The keyboard was placed on the table (recall the keyboard had a built-in 15° angle of inclination) and could be adjusted fore and aft to suit the subject's comfort. The only constraints were that the keyboard could not be angled to the side and that it had to stay in-line with the subject's right-arm position, paralleling his centerline to the CRT.

The experimental task was to key-in a list of alphanumeric strings. Accuracy was stressed over speed; thus, the subjects were permitted (and instructed) to correct errors. Subjects were permitted to use only one hand to operate the keyboard, their right one.

a. Instruction

After the subject was seated, he was first asked to position himself and the keyboard as described above. Instructions were then read to the subject (Appendix A) which included familiarization with the layout of the keyboard he was to use, and instruction as to the keying logic associated with the keyboard. The instruction included a demonstration by the experimenter of both the alphabetic and numeric Logics, as well as pre-training practice by the subject. Also explained at this time was the format of the typed list of alphanumeric strings the subject would be keying-in, the format of the CRT, and the procedure/function of the 'special' function keys. Subjects were permitted to ask questions regarding the keyboard Logic, display format, or task procedures, prior to the formal training period.

b. Training

After a short break, the subject was presented a list of alphanumeric strings for training. The list contained all alphabetic and numeric characters (36 total) with their frequency of occurrence as near to uniform as possible. The training list and frequency of occurrence of the characters is shown in Figure 14 and Table 2, respectively.

Each subject trained to an accuracy criterion. While both speed and accuracy are relevant criteria, keying accuracy was selected because of the importance of accurate entry of information into aircraft subsystems. For example, an error in entering a navigation waypoint could cause the aircraft to be flown off the desired course, with possibly fatal consequences. When the subject keyed the list twice (in succession), correcting any errors, he was assumed to have learned the logic and the task procedure.

c. Data Collection

The subject's experimental session concluded with the collection of test data. The subject was reminded that accuracy was more important than speed, once again. Subsequently, the subject was provided a list of alphanumeric strings to be keyed for the data collection task. The list was formatted identically to the training list, but was longer. This list and the frequency of occurrence of the alphabetic and numeric characters is shown in Figure 15 and Table 3, respectively.

The data collection was completed when the subject had completed his three replications. The time between replications was selected by the subject, but was not permitted to exceed ten minutes. On the average, the entire session with a subject did not last for more than 1 hour and 30 minutes.

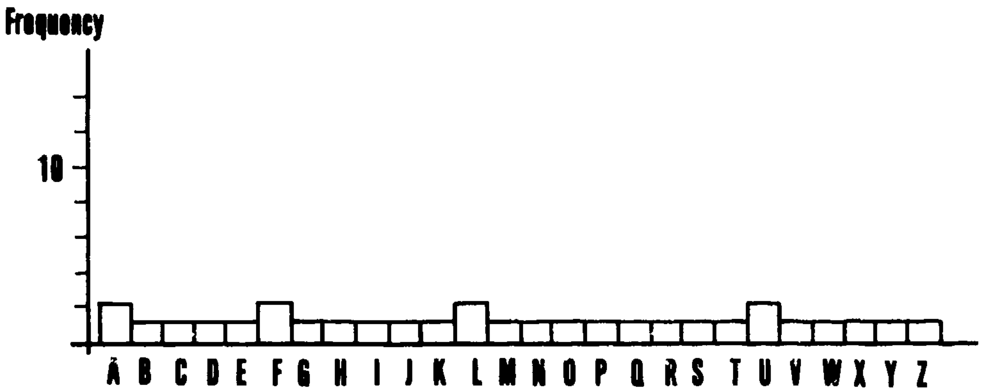
At the conclusion of the experimental session, the subject was asked to complete the questionnaire shown in Appendix B.

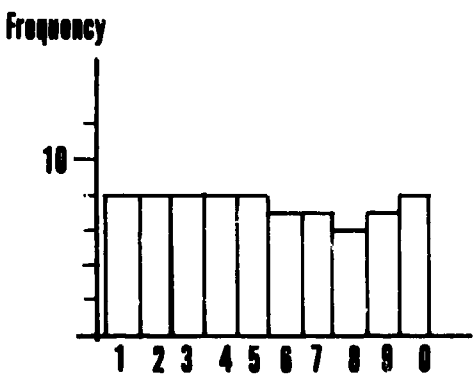
Column A	Column B	Column C
N403629 W851734	1058	000
MAPYS	2433	189
RGI	4679	256
B216 D57	6893	274
JOQEL	FL345	268
TUCK	17909	157
ZAFUX	18036	097
HEV	21234	455

Figure 14. Training List

TABLE 2

FREQUENCY DISTRIBUTION OF TRAINING LIST CHARACTERS



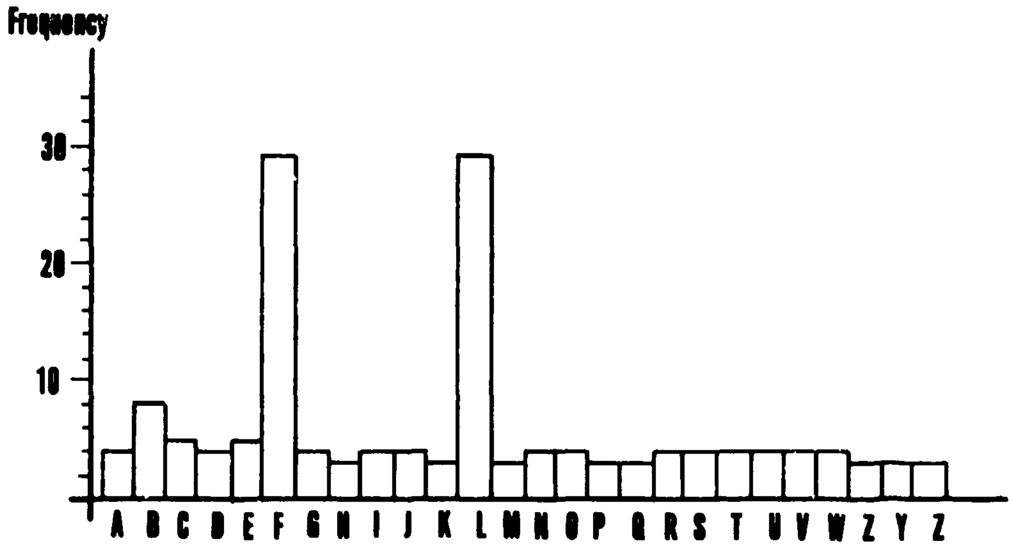


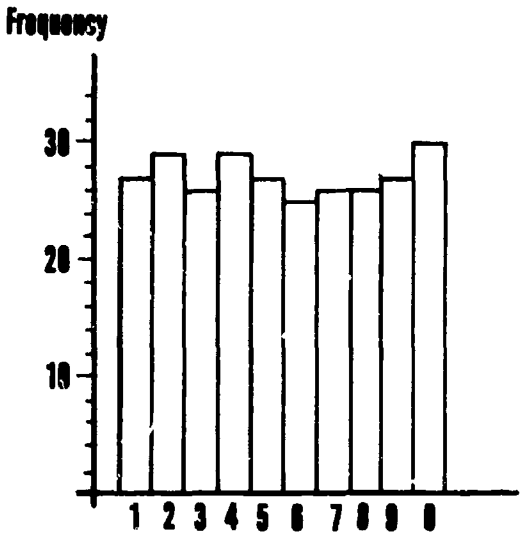
COLUMN A	COLUMN B	COLUMN C
N374518 W642309	2345	678
RZI	10967	432
ABC	15890	510
B310 D67	FL200	333
JUVTY	FL222	196
VGJ	FL218	175
S440525 E493732	FL344	197
POLK	FL458	604
CXQCK	50689	567
ABQ	FL495	495
B166 D88	37890	421
RGS	69877	637
TWINE	FL200	510
ABZ	FL328	483
B299 D157	61945	278
HRMZ	27845	619
N251908 W062847	FL483	328
HUQLS	FL510	200
JGV	63777	698
HOFF	42190	378
EMG	FL495	495
MUPPY	56789	506
JUVTY	FL604	458
LOK	FL197	344
S310758 E012345	FL175	218
FOXX	FL196	222
RCI	FL333	200
ABC	51090	158
B667 D899	43267	109
TWINE	67845	203

Figure 15. Data Collection List

TABLE 3

FREQUENCY DISTRIBUTION OF DATA LIST CHARACTERS





SECTION III

RESULTS

Results are presented for keying accuracy measures first, followed by keying speed measures. Within each of these categories, the results are presented in the order in which the data were analyzed; that is:

- Numeric Performance
- Alphabetic Performance
- Alphabetic/Numeric Transition Performance (accuracy, only)
- Repeated Cluster Performance
- Estimated List Performance

A two-way Analysis of Variance (ANOVA) was used as the test for significant differences resulting from Logic or Replication effects. To use this ANOVA, the data in each cell of Figure 12 were reduced to a mean value. These mean values were then used to conduct the ANOVA. All ANOVAs were tested at the α = .10 level.

1. KEYING ACCURACY

The results reported for the statistical analysis of keying accuracy were obtained using an arcsine transformation to normalize the collected data.

a. Numerics

The mean values of numeric keying accuracy are plotted in Figure 16, for each Logic and Replication. Also, 1 sigma ranges are shown for each mean. A two-sample t-test between the mean numeric keying accuracy for Logic 3 and Logic 1 was performed in order to affirm the experimental assumption that subject groups were homogeneous. The data for these Logics were used because they were the apparent slowest and

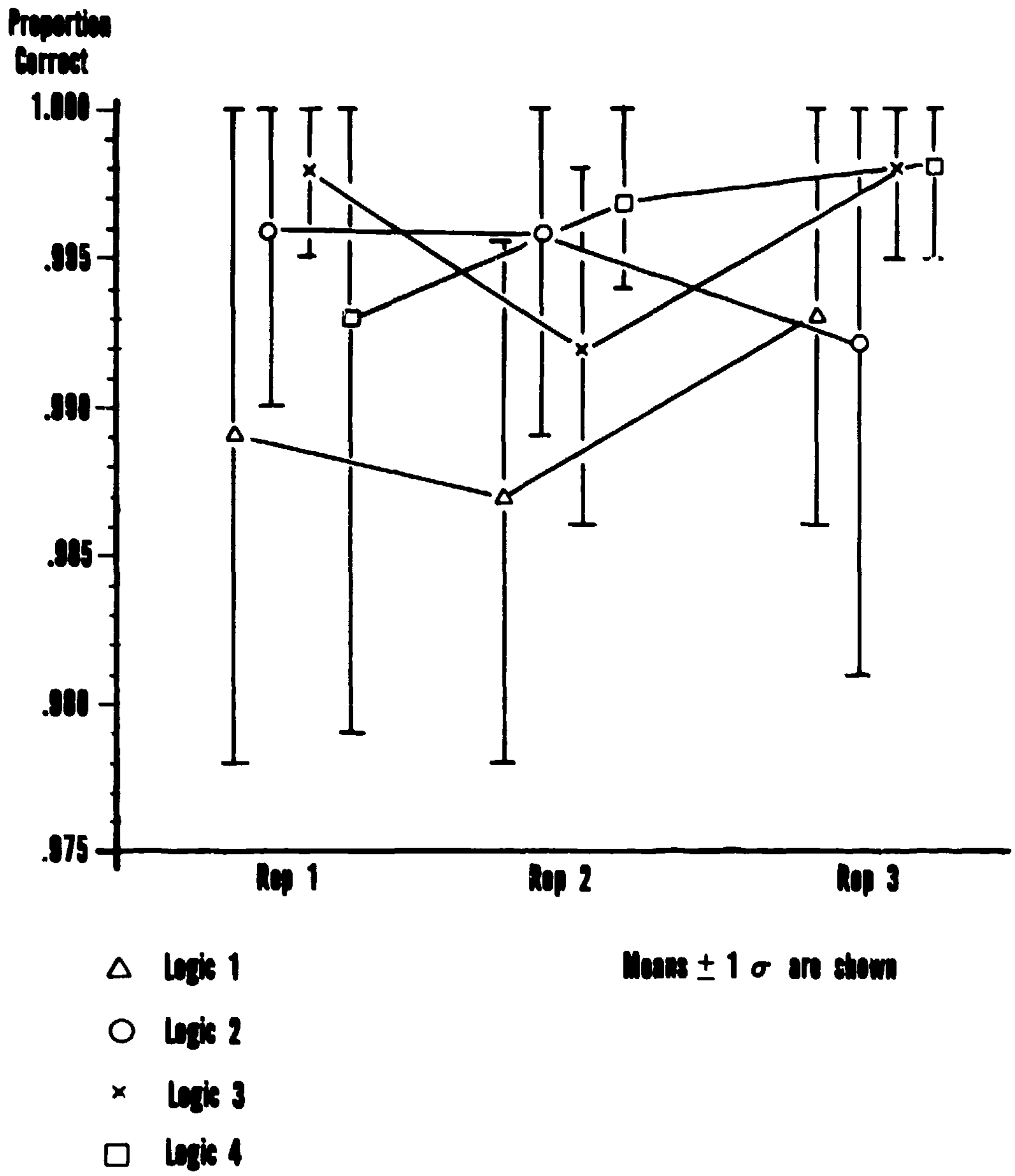


Figure 16. Mean Numeric Keying Accuracy (Proportion Correct) by Logic and Replication

fastest, and no statistical difference between these Logics would imply a lack of statistical difference between any of the Logics (i.e., all numeric performance is equal). The results of the t-test procedure contradicted this assumption by finding a significant difference between Logics 1 and 3, $p < .008$. However, although Logic 1 appears to have consistently poorer performance than Logics 3 and 4, and poorer performance than Logic 2 in all but the third Replication, from a practical viewpoint the Logic had no effect on numeric keying accuracy. This result is supported by the difference between the means for Logic and 1 and the other Logics which is between .001 and .010, for a difference amounting to between 1 error in 1000 and 1 error in 100. Also, the overlapping distributions provide further support to the result of no practical difference for mean numeric keying accuracy. A two-way (Logic x Replication) ANOVA supports this interpretation by finding no difference between the Logics with regards to keying accuracy.

b. Total List

The total list mean keying accuracy, with 1 sigma range, for each Logic and Replication is plotted in Figure 17. Logic 4 showed consistently the most superior performance and Logic 1 showed consistently lowest performance. Total list keying accuracy for Logics 2 and 3 are less consistent. A two-way (Logic x Replication) ANOVA showed a significant difference between Logic means, $F(3,6) = 17.66$, $p < .002$. The Duncan Multiple Range Test ($\alpha = .05$, df = 6) on these means revealed Logic 1 was significantly different from Logics 2, 3, and 4; Logic 4 was significantly different from Logics 1, 2, and 3; and no difference between Logics 2 and 3.

Results of a two-way (Replication x Subject) ANOVA testing for a Replication effect within each of the Logics revealed no significant effect for any of the Logics.

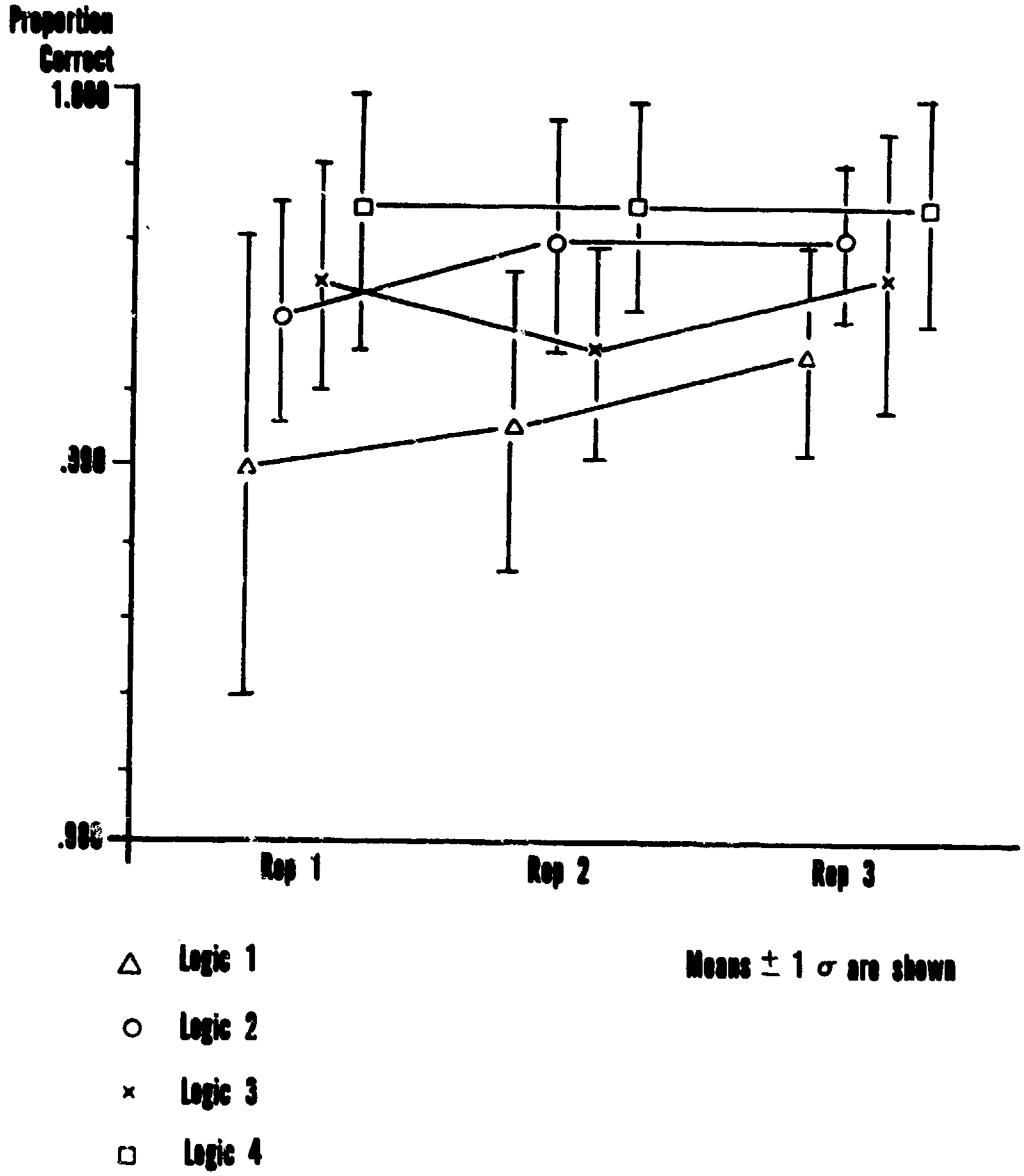


Figure 17. Mean Total List Keying Accuracy (Proportion Correct) by Logic and Replication

c. Alphabetics

Values of mean alphabetic keying accuracy for each Logic and Replication are plotted in Figure 18, along with the 1 sigma range about each mean. Consistently superior performance is exhibited by Logic 4, with the poorest performance consistently shown by Logic 1. The data for Logics 2 and 3 are not as consistent, but Logic 2 appears to be superior to Logic 3.

A two-way (Logic x Replication) ANOVA confirmed the significant Logic effect $F(3,6) = 20.46$, $p < .001$, and a significant Replication effect, $F(2,6) = 4.10$, $p < .075$. Duncan's Multiple Range Test ($\alpha = .05$, df = 6) on the Logic means showed Logic 1 significantly different from all other Logics, Logic 4 significantly different from all other Logics, and no difference between Logics 2 and 3.

In order to test for a Replication effect within each Logic, a two-way (Replication x Subject) ANOVA was performed for each Logic. Logics 1, 3, and 4 each showed no significant difference across Replications. Logic 2 had a significant Replication effect, $F(2,12) = 4.89$, $p < .028$. A Duncan's Multiple Range Test was subsequently performed on the Replication means for Logic 2, in order to determine where the difference occurred. The results showed a significant difference ($\alpha = .05$, df = 12) between Replication 1 and Replications 2 or 3. Further, the results showed no significant difference between Replications 2 and 3.

d. Alphabetic/Numeric Transitions

The means for each Logic and Replication for alphabetic/numeric transition keying accuracy data, along with the 1 sigma range about each mean, are plotted in Figure 19. A two-way (Logic x Replication) ANOVA showed no difference between means for either Logic or Replication effects.

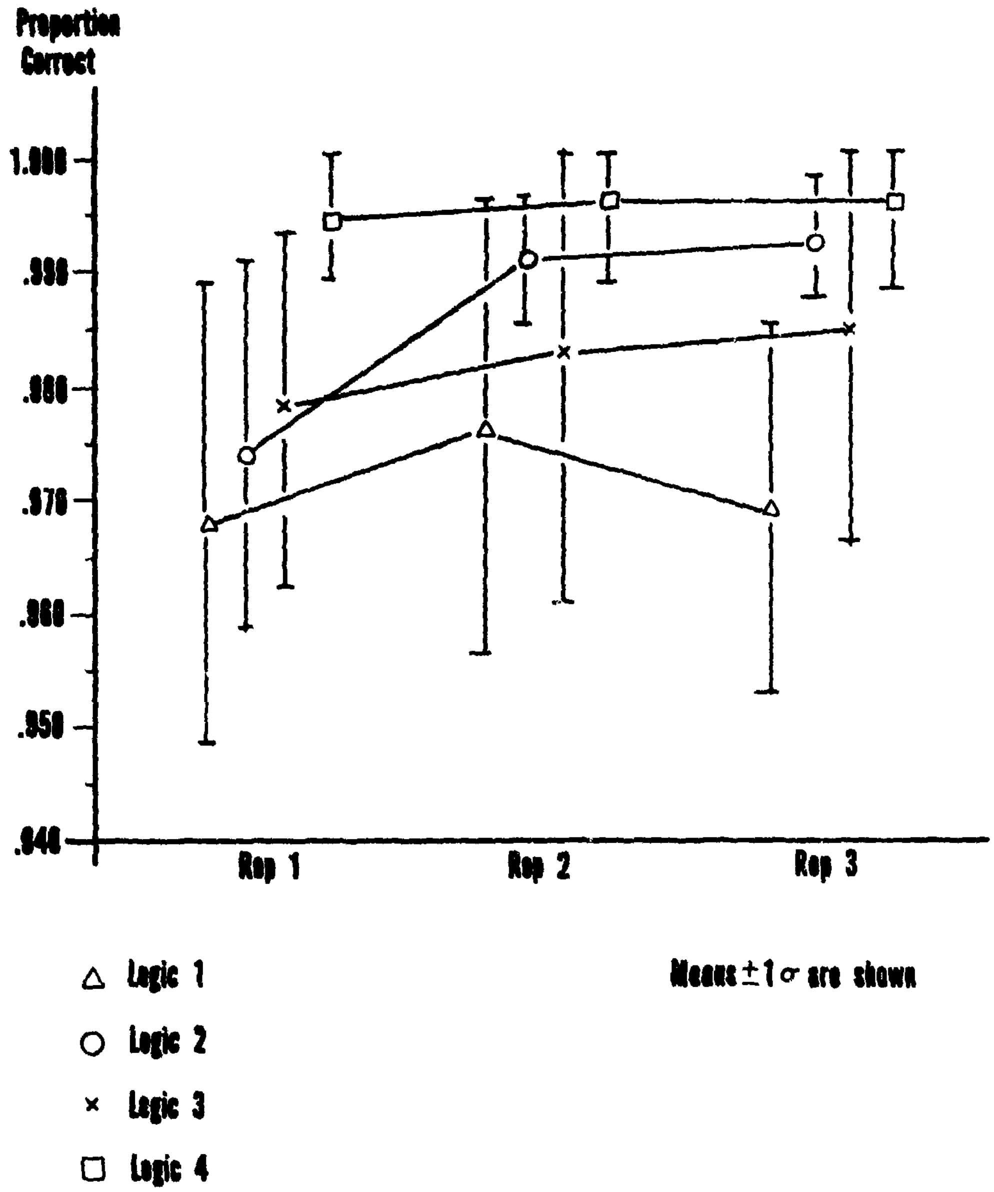


Figure 18. Mean Alphabetic Keying Accuracy (Proportion Correct) by Logic and Replication

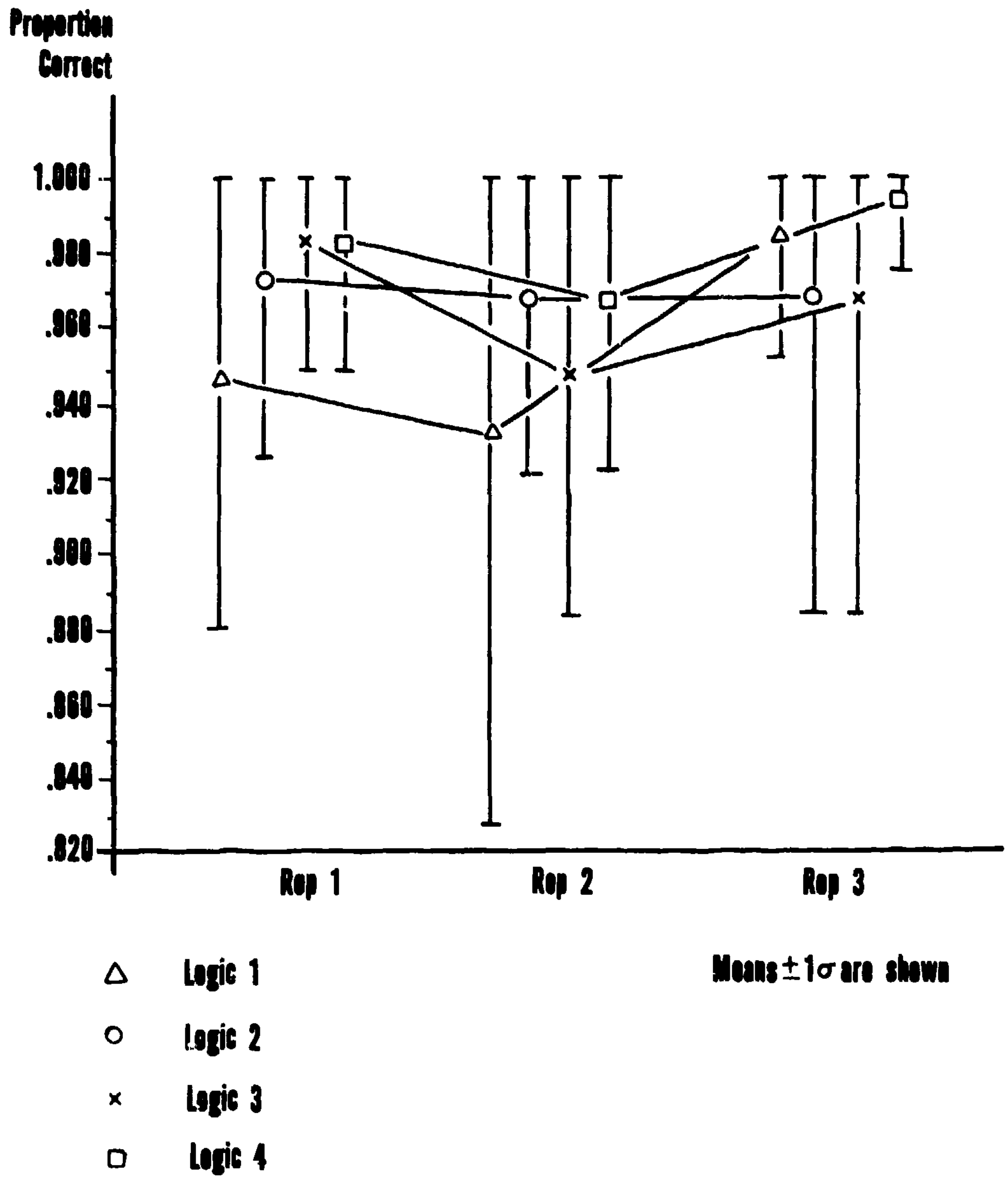


Figure 19. Mean Alphabetic/Numeric Transition Keying Accuracy (Proportion Correct) by Logic and Replication

e. Repeated Clusters of Characters

With regard to subject performance on alphabetic and/or numeric clusters that were repeated in the data collection list, mean numeric keying accuracy and mean alphabetic keying accuracy were extracted for the initial and repeated occurrences. These data are plotted for each Replication by Logic in Figures 20 and 21, respectively.

Numeric keying accuracy, while exhibiting different trends across Replications for each of the four Logics, showed no practical significant difference within the Replication. This is ascertained from Figure 20, where the data points correspond to either zero errors (proportion correct = 1.000) or one error (proportion correct = .952). Another result apparent in Figure 20 is the consistency of numeric keying accuracy for Logics 3 and 4, as compared with either Logic 1 or Logic 2.

Alphabetic keying accuracy for repeated clusters also exhibited various trends across the Replications. Logic 1 showed a larger proportion correct on the initial occurrence of the repeated cluster, for each of the three Replications. Also, Logic 1 showed an improvement in performance across Replications for the repeated clusters. Logics 2 and 3 showed performance that tends to hover between a proportion correct of .978 and .989, with no consistent trend across Replications. Logic 4, on the other hand, showed consistent performance both within and across Replications.

f. Summary

Numeric keying accuracy was used to test for homogeneity of the subjects. A two-way (Logic x Replication) ANOVA supports the homogeneous assumption, as does visual inspection of the data. Total list keying accuracy shows significant differences such that Logic 4 accuracy > Logic 2 or 3 accuracy > Logic 1 accuracy. Alphabetic keying accuracy shows

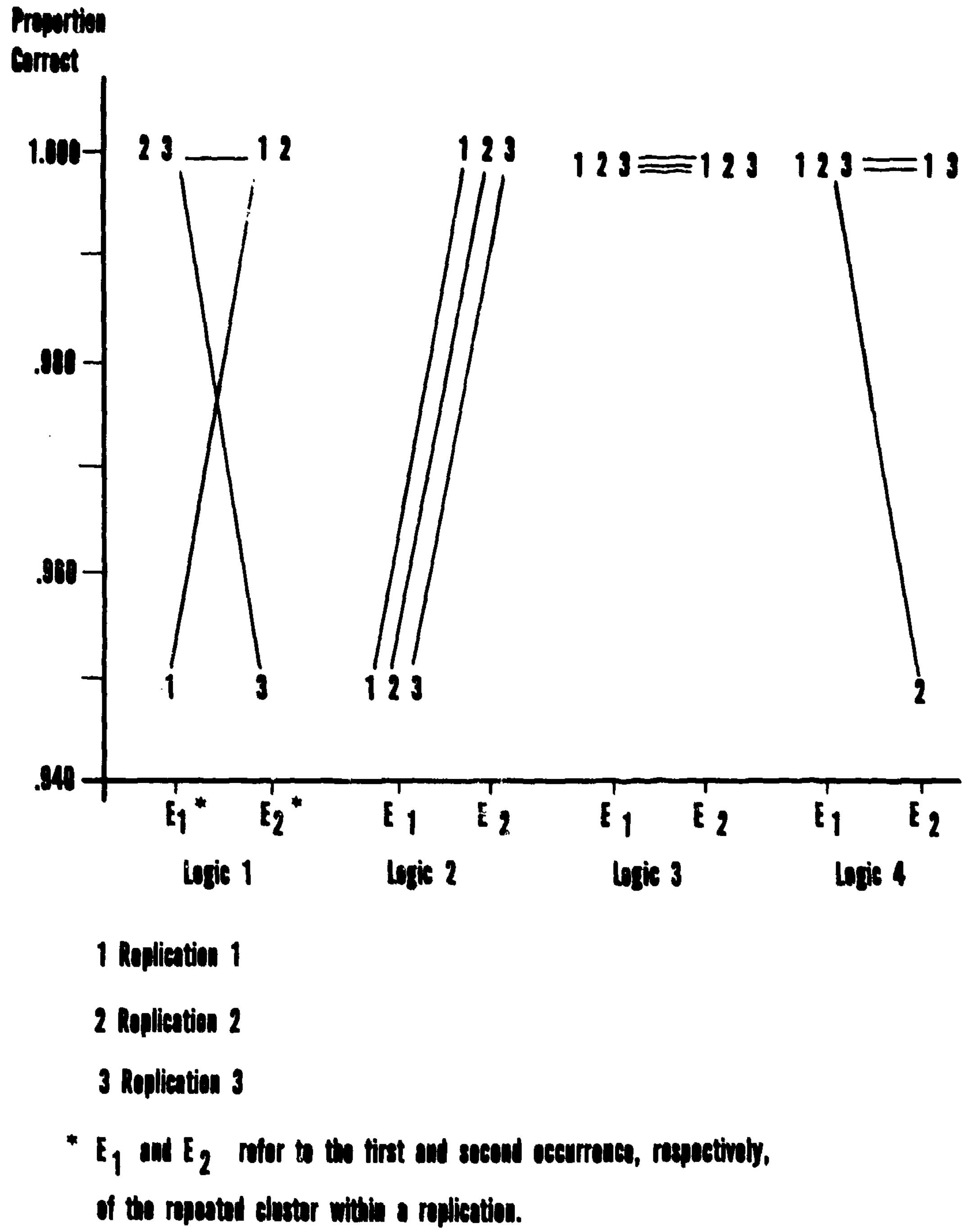


Figure 20. Mean Numeric Keying Accuracy (Proportion Correct) on Repeated Clusters for all Replications of each Logic

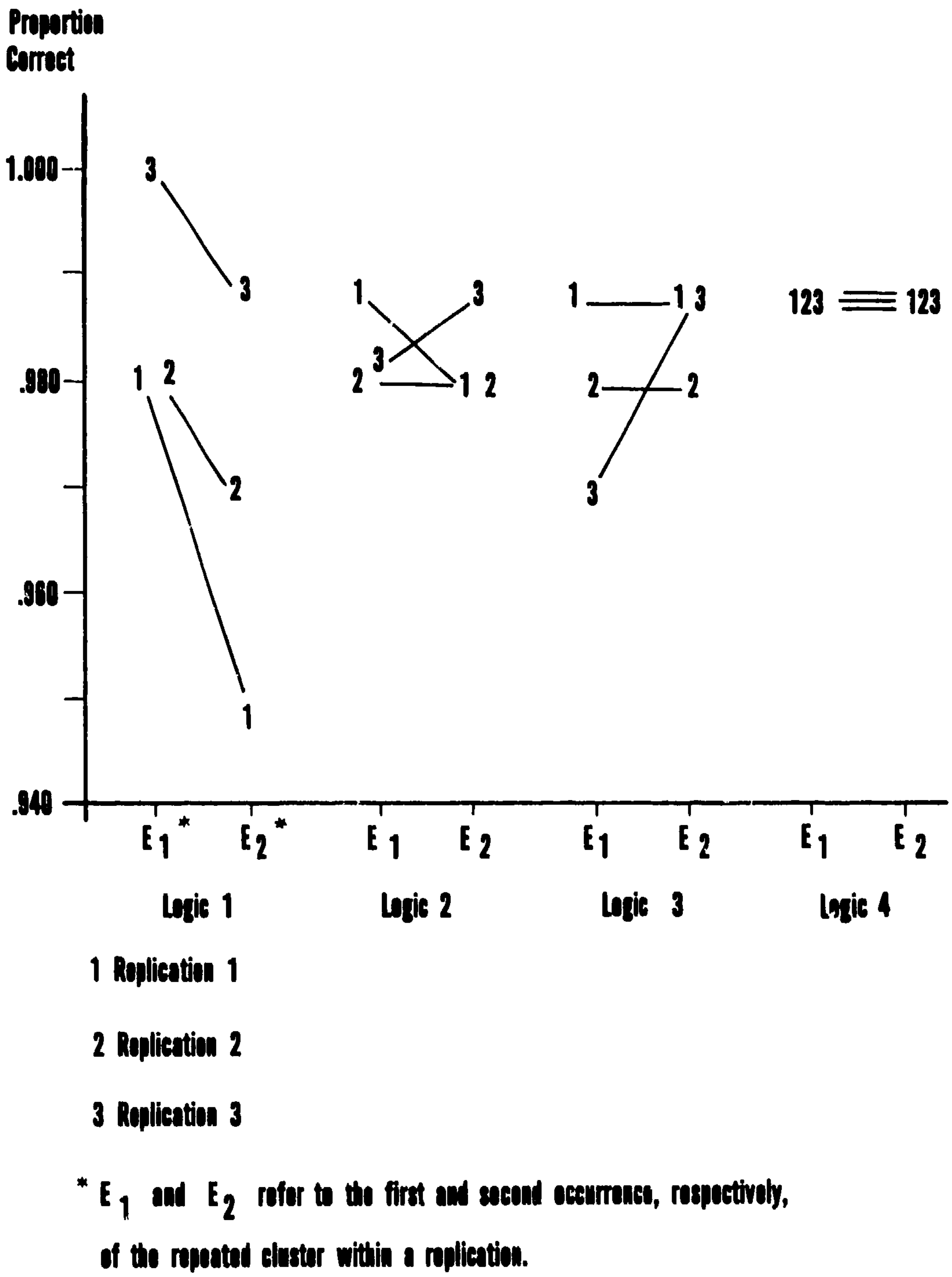


Figure 21. Mean Alphabetic Keying Accuracy (Proportion Correct) on Repeated Clusters for all Replications of each Logic

identical significant differences. Alphabetic/Numeric Transition keying accuracy shows no significant difference among Logics. The accuracy trends of clusters of alphanumeric characters repeated within a replication are inconclusive regarding within replication learning.

2. KEYING SPEED

The measure for keying speed used throughout the analysis was seconds, recorded to the thousandth of a second (.001 second or 1 millisecond).

a. Numerics

Mean numeric keying time, along with the one sigma range, for each Replication of each Logic is plotted in Figure 22. A two-sample t-test of the means for Logics 3 and 4 was performed in order to, again, confirm the homogeneity of the subjects. The result showed no significant difference between these means, which can be interpreted as the data for four Logics are from the same population (i.e., homogeneous subjects).

A two-way (Logic x Replication) ANOVA showed a significant Replication effect, $F(2,6) = 14.12$, $p < .005$, on numeric keying time. Each Logic was then analyzed by a two-way (Replication x Subject) ANOVA in order to locate which Logics had Replication effects. The results indicated significant effects for Logic 1, $F(2,12) = 10.82$, $p < .002$, Logic 2, $F(2,12) = 14.62$, $p < .006$, and Logic 4, $F(2,13) = 7.67$, $p < .007$. Duncan's Multiple Range Test was performed on these Logics and significant differences ($\alpha = .05$, df = 12) in performance were found for the second versus third Replication of both Logic 1 and 2. Logic 4, however, showed no difference in performance for the second versus third Replication.

b. Total List

Mean keying times and one sigma ranges for the total list are plotted in Figure 23 by Logic and Replication. As shown, the means for Logics 1, 2, and 3 are almost identical within each Replication. These same three Logics show similar improvement across the three

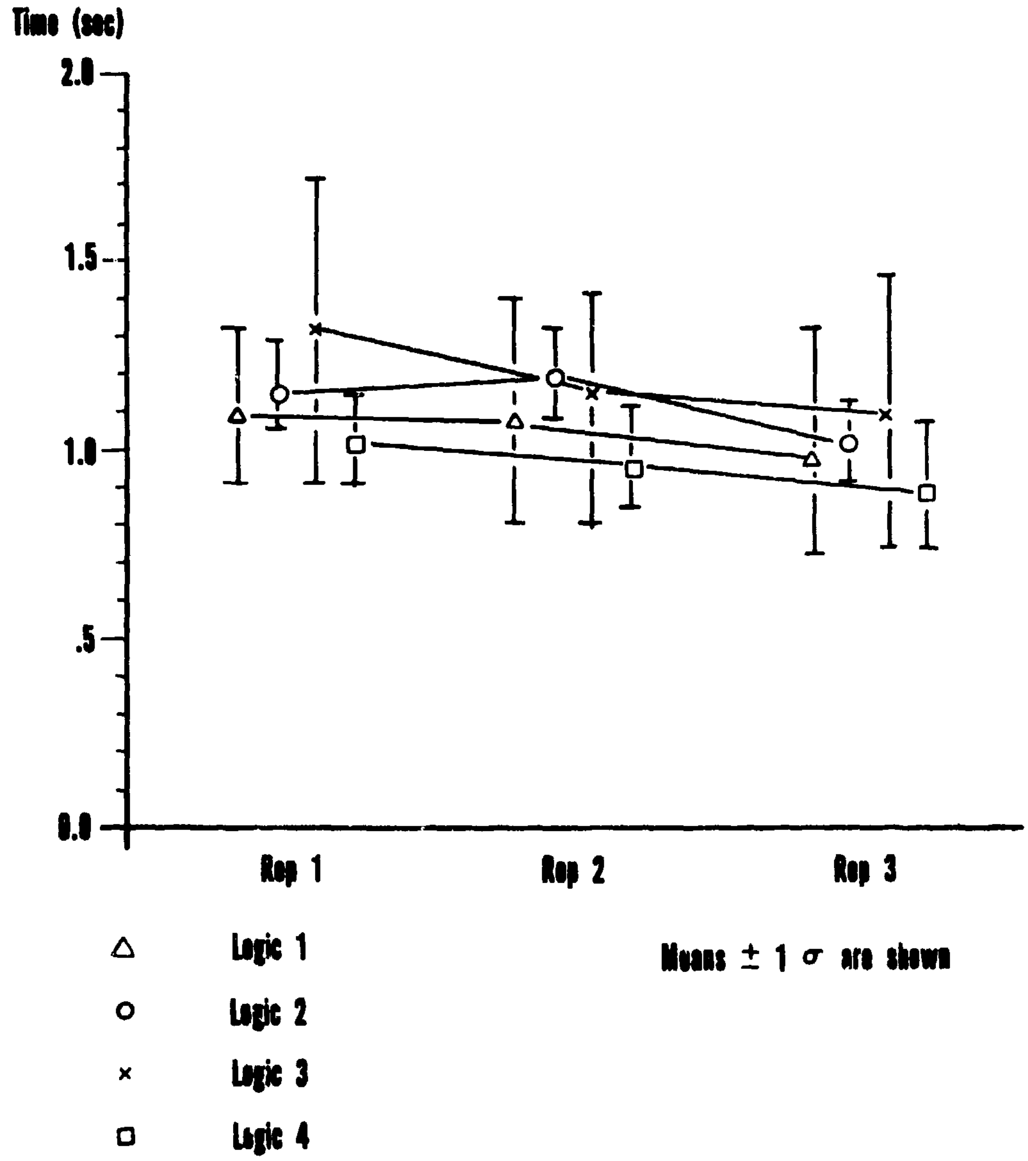


Figure 22. Mean Numeric Keying Time (Seconds) by Logic and Replication

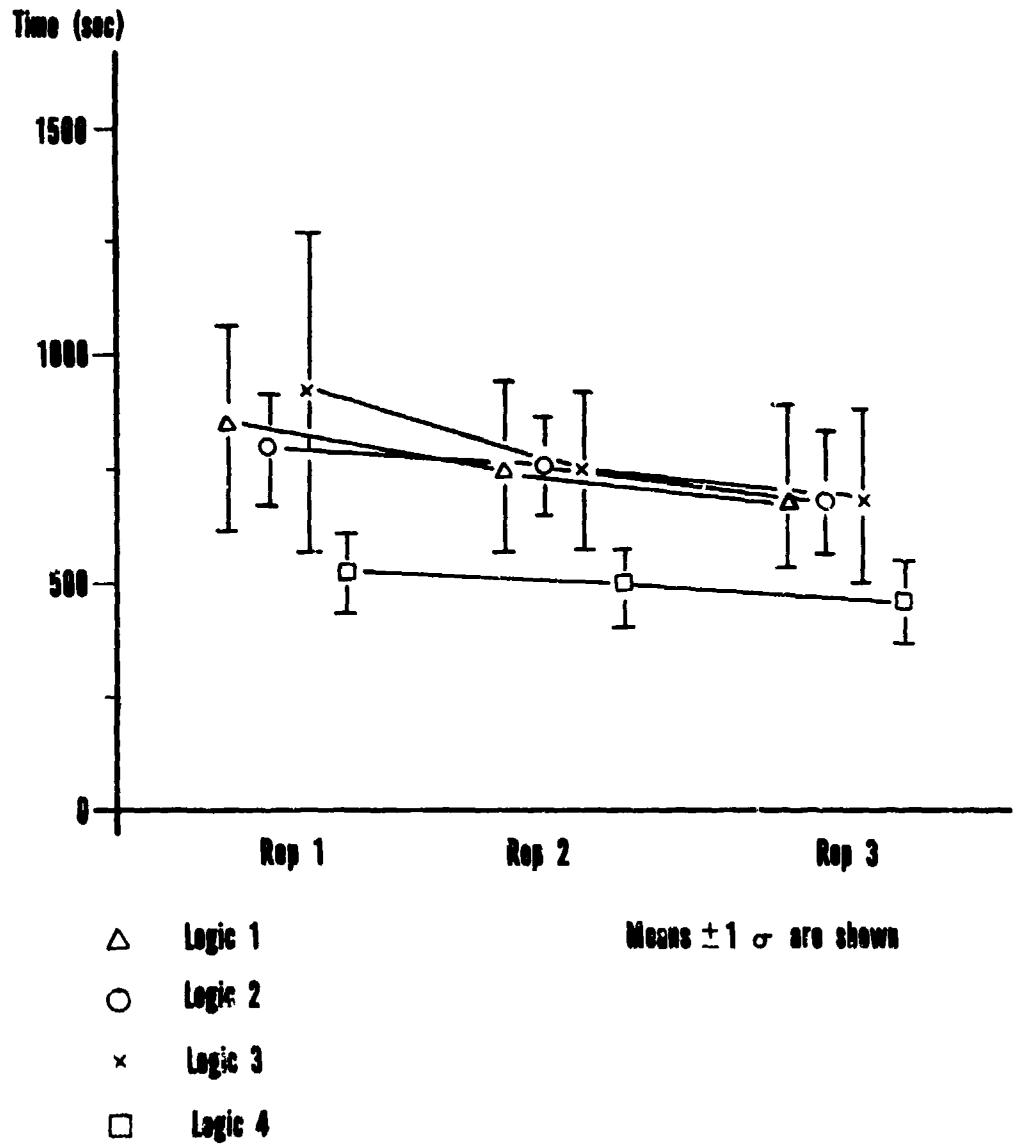


Figure 23. Mean Total List Keying Time (Seconds) by Logic and Replication

Replications. Also, easily seen is the consistent superiority of Logic 4, which shows improvement across the Replications paralleling that of the other Logics. A two-way (Logic x Replication) ANOVA confirmed these results as significant for both Logics, $F(3,6) = 41.34$, $p < .002$, and Replications, $F(2,6) = 17.47$, $p < .003$. Duncan's Multiple Range Test on Logic means produced the expected results of no difference between Logics 1, 2, and 3, and a significant difference ($a = .05$, df = 6) between these three Logics and Logic 4.

In order to further analyze the Replication effect, two-way (Replication x Subject) ANOVAs were performed on the total list keying time data of each Logic. All four Logics exhibited significant Replication effects with $F(2,12) = 25.72$ and $p < .001$ for Logic 1, $F(2,12) = 18.93$ and $p < .002$ for Logic 2, $F(2,12) = 10.48$ and $p < .002$ for Logic 3, and $F(2,12) = 14.29$ and $p < .0007$ for Logic 4. Duncan's Multiple Range Test on Logic 1 data revealed a significant difference between each Replication. Duncan's Test on Logic 2 produced identical results, that is, mean total list keying time performance on each Replication was significantly different from the performance on the previous Replication. Duncan's Test on Logic 3, however, revealed a significant difference between Replications 1 and 2, and no difference in the performances on Replications 2 and 3. Logic 4, according to Duncan's Test, showed significant differences between all Replications for mean total list keying time.

c. Alphabetics

Results for alphabetic keying time are presented for each Logic, as this reflects the performance differences between Logics to key-in an alphabetic character. This parameter, however, is biased in favor of Logic 4 because of the different number of strokes required to key-in an alphabetic character (3 strokes for Logics 1 and 2, 2 or 3 strokes for Logic 3, and 1 stroke for Logic 4). In order to remove this bias, stroke times were computed for each Logic and subsequently analyzed. The results of the analysis of alphabetic stroke time are also presented.

The means and one sigma ranges for alphabetic character keying time are plotted for each Logic and Replication in Figure 24. As anticipated, the performance of Logic 4 is consistently and uniformly superior to the other Logics. A two-way (Logic x Replication) ANOVA confirmed the existence of a significant difference, $F(3,6) = 51.49$, $p < .0001$, resulting from a Logic effect. Duncan's Multiple Range Test on Logic means showed no difference between Logics 1, 2, and 3, while Logics with regard to alphabetic character keying time.

The previous ANOVA also found a significant Replication effect, $F(2,6) = 11.46$ and $p < .008$. Each Logic was individually analyzed using a two-way (Replication x Subject) ANOVA in order to determine the presence of a Replication effect. As expected from Figure 24, all Logics had significant Replication effects, $F(2,13) = 23.24$, $p < .0001$ for Logic 1, $F(2,12) = 20.00$, $p < .0002$ for Logic 2, $F(2,12) = 8.95$, $p < .004$ for Logic 3, and $F(2,12) = 16.40$, $p < .004$ for Logic 4. Duncan's Multiple Range Test showed significant differences ($\alpha = .05$, df = 12) between all Replications for Logics 1, 2, and 4. Logic 3 showed a significant difference ($\alpha = .05$, df - 12) between Replications 1 and 2 only, however.

The means for alphabetic stroke time, and their 1 sigma ranges, are plotted in Figure 25 by Logic and Replication. As the Figure shows, Logics 1 and 2 showed the smallest stroke times across all Replications, with Logic 4 consistently the slowest. As the data suggest, a two-way (Logic x Replication) ANOVA showed both a Logic effect, $F(3,6) = 23.00$, $p < .001$, and a Replication effect, $F(2,6) = 11.70$, $p < .008$. Duncan's Multiple Range Test on the Logic means produced expected results of no significant difference between Logics 1 and 2 or Logics 3 and 4. A significant difference ($\alpha = .05$, df = 12) was detected, however, between these pairs.

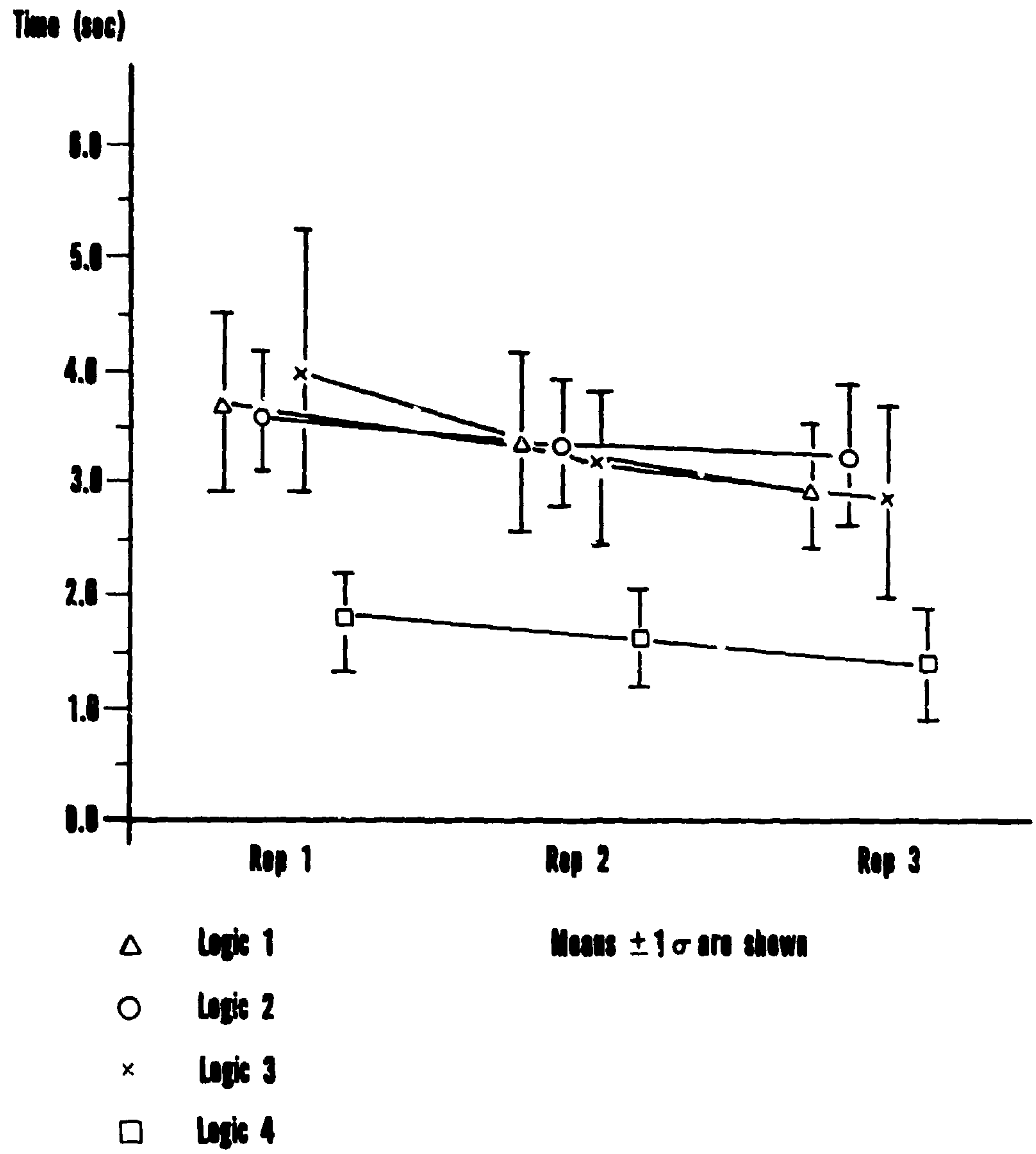


Figure 24. Mean Alphabetic Character Keying Time (Seconds) by Logic and Replication

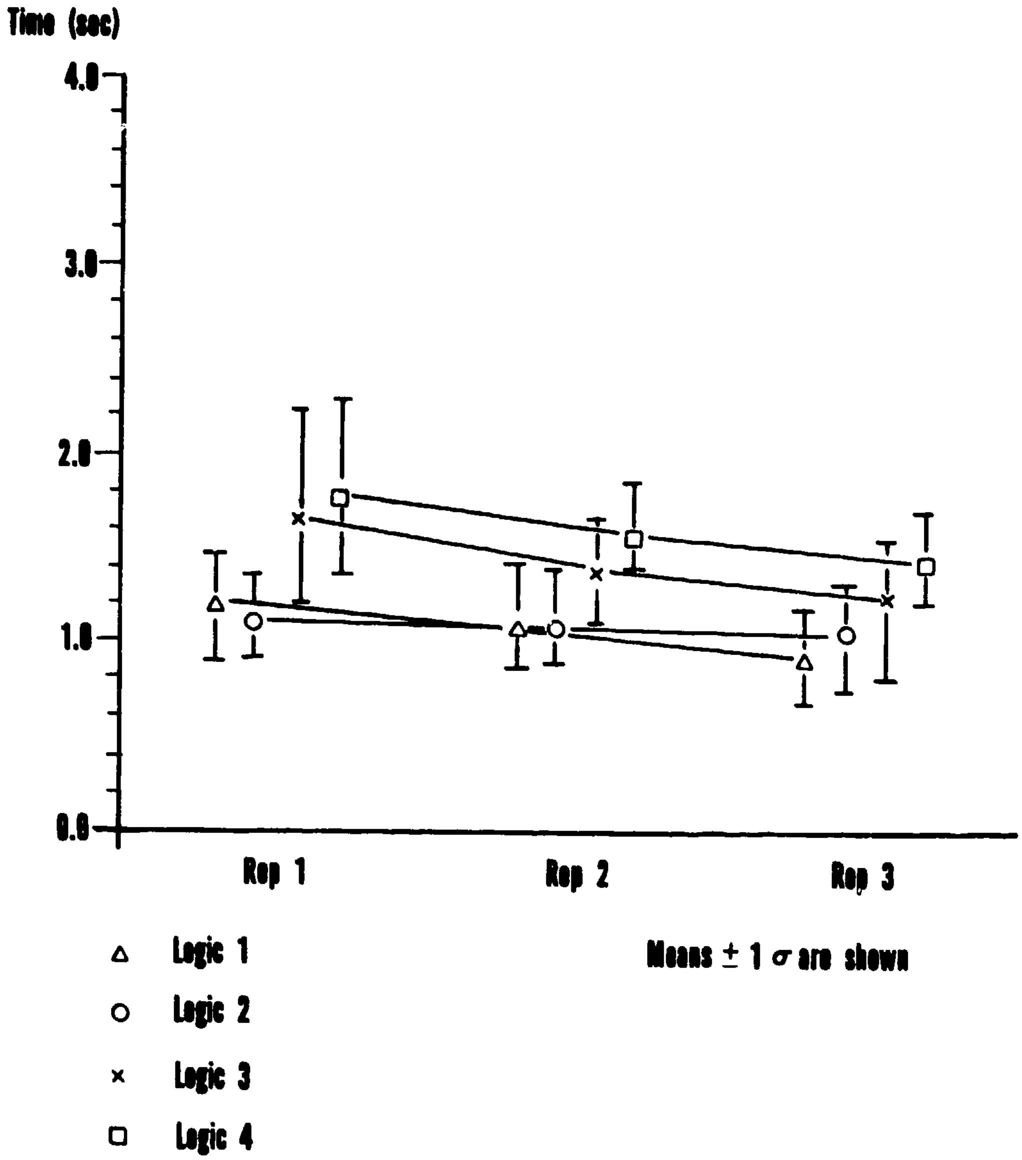


Figure 25. Mean Alphabetic Stroke Time (Seconds) by Logic and Replication

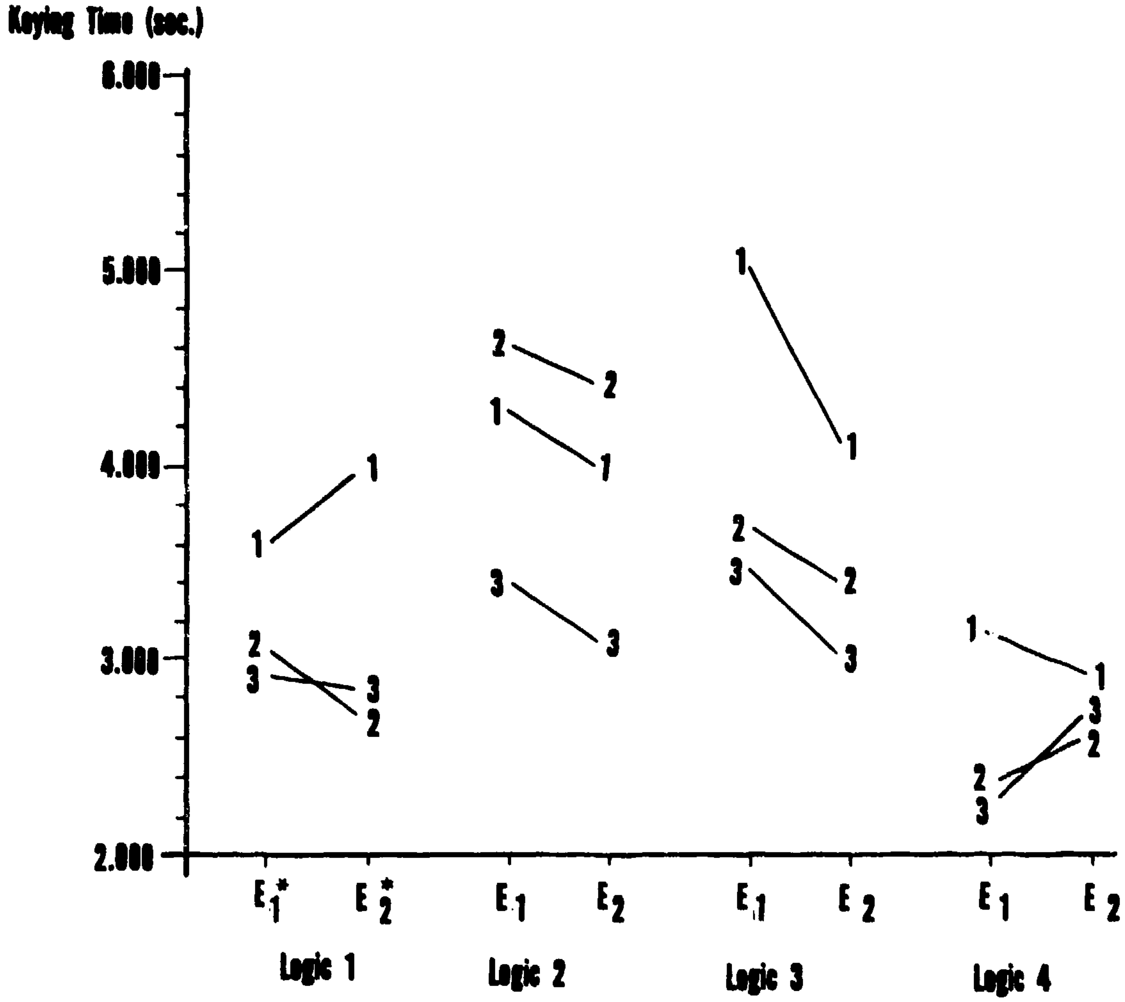
As a result of the Replication effect, two-way (Replication x Subject) ANOVAs were performed on the data for each Logic in order to specify this effect. From this analysis, significant Replication effects were found for Logic 1, $F(2,12) = 28.38$, $p < .0001$, Logic 3, $F(2,12) = 14.48$, $p < .0006$, and Logic 4, $F(2,12) = 16.40$, $p < .0004$. Duncan's Multiple Range Test performed on these Logics revealed significant differences ($\alpha = .05$, df = 12) between all Replications for both Logics 1 and 4. Logic 3 had a significant difference ($\alpha = .05$, df = 12) between Replications one and two, but no difference between Replications two and three.

d. Repeated Clusters of Characters

Mean numeric keying time and alphabetic stroke time for both the initial and repeated occurrence of alphanumeric clusters are plotted in Figures 26 and 27, respectively, for all Logic and Replications.

The data for numeric keying time show both within-Replication and across-Replication improvement for Logics 2 and 3. The data for Logics 1 and 4 show across-Replication improvement for numeric keying time; however, within-Replication performance with these Logics shows no consistent improvement. Also noticeable is the magnitude of the across-Replication improvement for Logics 2 and 3, as compared to Logics 1 and 4. These differences are consistent with the previously presented data of mean numeric keying time for all numerics, in that Logics 1 and 4 had shorter, similar keying times and exhibited a similar across-Replication improvement. The previous data for Logics 2 and 3 are also consistent with these across-Replication results in that Logics 2 and 3 exhibited similar keying times which, across-Replications, approached but did not achieve the keying times of Logics 1 and 4.

The data for alphabetic stroke time associated with repeated clusters also exhibit across-Replication improvement for all Logics.



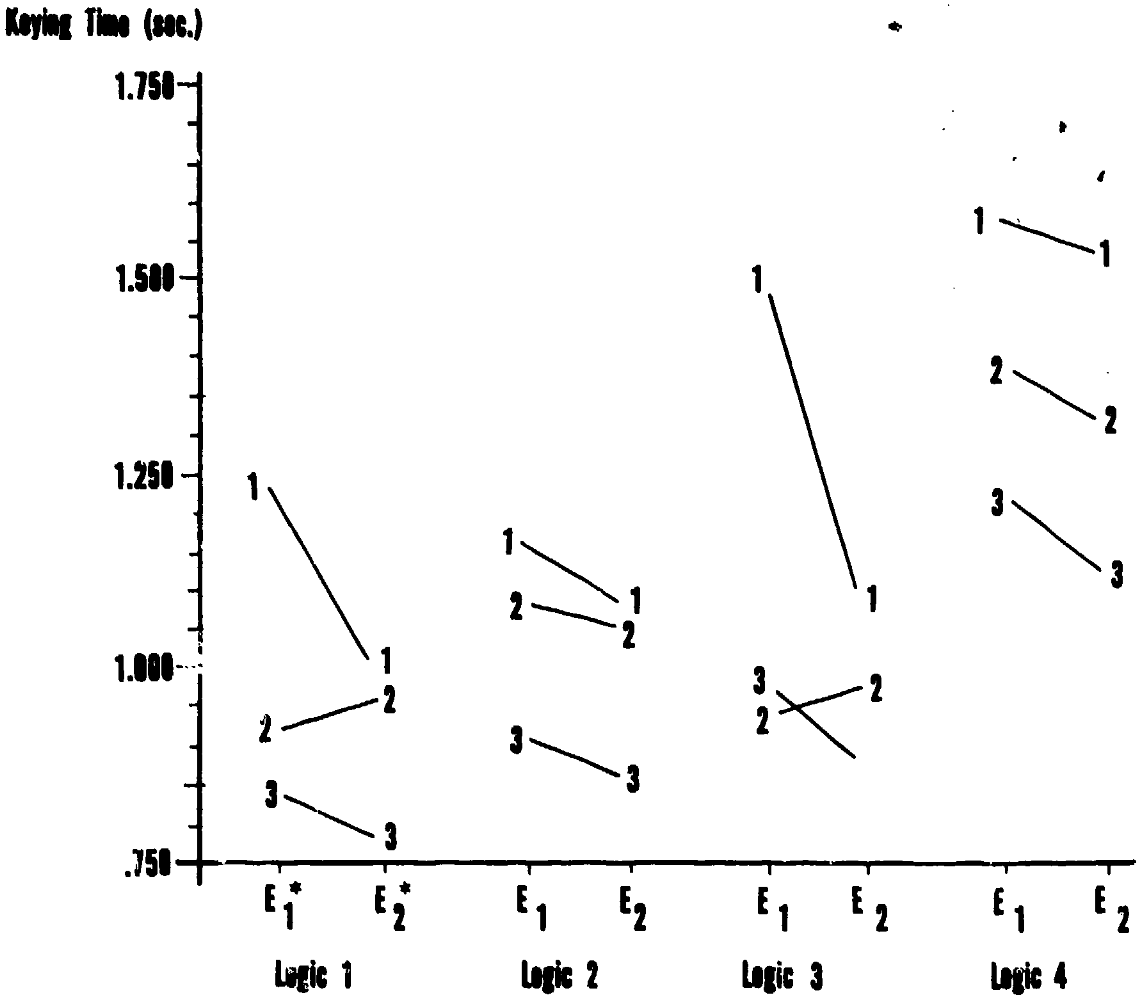
1 Replication 1

2 Replication 2

3 Replication 3

* E_1 and E_2 refer to the first and second occurrence, respectively, of the repeated clusters within a replication.

Figure 2[illegible]. Mean Numeric Keying Time (Seconds) on Repeated Clusters for all Replications of each Logic



1 Replication 1

2 Replication 2

3 Replication 3

* E_1 and E_2 refer to the first and second occurrence, respectively, of the repeated clusters within a replication.

Figure 27. Mean Alphabetic Stroke Time (Seconds) on Repeated Clusters for all Replications of each Logic

Within-Replication improvement of alphabetic stroke time is consistently present in Logics 2 and 4, and generally present in Logics 1 and 3. These data also are consistent with the previous data presented for alphabetic stroke time associated with all alphabetic clusters. As before, Logic 2 initially had the shortest stroke time, but was outperformed by Logic 1 at the completion of the session. Also, as before, Logic 4 exhibited the slowest stroke time for each Replication.

e. Summary

Numeric keying time, like numeric keying accuracy, was used to test for subject homogeneity. Statistical analysis of the data confirms this assumption, as does visual inspection. Total list keying time data show no significant difference among Logics 1, 2, and 3, but the data do show that Logic 4 is significantly different from the other three. Alphabetic character keying time shows identical results. Alphabetic stroke time data shows no difference between Logics 1 and 2 or Logics 3 and 4. A significant difference was found between these pairs, (e.g., Logic 2 significantly different from Logic 3), however. The trends in keying time for alphanumeric clusters repeated within a replication generally show some improvement of keying time both within and across replications of a Logic.

SECTION IV

DISCUSSION OF RESULTS

The results presented previously indicate both keying accuracy and keying speed are affected by the Logic condition. Keying speed appears most variable, however, which was expected due to the instructions given the subjects to key-in the list accurately. Also, the results show differences in the pattern of performance improvement across Replications, which varied for both the Logic condition and performance measure considered. These and other results are discussed in this section.

Each Logic condition used a specific keyboard design (refer to Section II) and as a result, the discussion of the results includes consideration of both the Logic condition and the keyboard design as potential sources of the performance differences observed. This section first discusses the Logic/Keyboard Design effects on keying accuracy, followed by a discussion of Logic/Keyboard Design effects on keying speed.

1. LOGIC/KEYBOARD EFFECTS ON KEYING ACCURACY

In addition to the results previously reported for keying accuracy, Appendix C provides additional data in the form of frequency histograms of errors associated with each cluster and with each specific alphanumeric character.

Numeric keying accuracy was one of the measures used to test the homogeneity of the sample population across Logics. This measure was most suited to this purpose because of the constancy of the keyboard designs regarding numeric arrangement. The results show no significant difference between the extreme means, which supports the homogeneity of the subjects. The results also show the subjects were following the instruction to perform accurately. Further, the results indicate the arrangement of the alphabetic characters on the keys had little, if any, impact on numeric keying accuracy.

The results for numeric keying accuracy are also consistent with previously reported research. Accuracy rates for this research were close to 99.5% correct. Previous studies have found accuracy rates, for the same key arrangement, of 99.0%+ (Reference 8), and 99.45% (Reference 7).

Further, the histograms of Appendix C show consistent results regarding the error frequency of each numeric character (i.e., all numeric characters had several errors). This trend is generally consistent across Logics with the numeric "1" being the notable exception. For Logics 1, 2, and 3, the number "1" was located on the upper-left corner key (an easily locatable position) and experienced no errors on any of the data collection replications. The number "1" for Logic 4, however, was imbedded in the top row and experienced four errors. This result illustrates the sensitivity of performance to design features of the keyboard.

The keying accuracy for the total list provides evidence for a Logic difference and varying learning patterns. The most notable in both these qualities is Logic 4 which is not only significantly different from the other Logics with regard to proportion correct, but Logic 4 also shows a fully learned pattern on all three Replications. The other Logics, while not statistically significant, show evidence of improving performance across the Replications. Examination of the histograms of error frequency by cluster in Appendix C, shows errors were generally made on the same clusters for all Logics, and that the source of difference among Logics was the frequency of these errors. This indicates a possible condition that some clusters were more difficult for one Logic than for another Logic. Subjects for all four Logics reported that the clusters which contained both alphabetic and numeric characters, as well as the "less pronounceable" clusters (e.g., CXQCK, HRMZ) were more difficult. These observations are generally supported by the histograms in Appendix C, which show frequent errors for the coordinates (e.g., N374518 W642309) and bearing/distances (e.g., B166 D88). This performance was consistent across all four Logics, indicating that these types of clusters are more difficult and not necessarily made so by the Logic 2.

Alphabetic keying accuracy for the four Logics shows basically the same pattern as total list accuracy, which tends to highlight alphabetic accuracy as the primary contributor to list accuracy. This interpretation is further strengthened by recalling that the other component of the list, namely numeric accuracy, was essentially equivalent for the four Logics investigated. Logic 4, again, shows a significant consistent superiority to the other Logics, while Logic 1 once again is the consistently poorest performing Logic. The histograms of Appendix C show Logic 4 as virtually error free (4 errors in 3192 alphabetic key-ins) and alphabetic errors in Logics 1, 2, and 3 spread across essentially all the characters.

The data of Appendix C also show results consistent with information provided on the questionnaire (Appendix B) regarding the difficulty of individual characters. Characters with a fairly high frequency of occurrence relative to the frequency of other characters (e.g., G and Q in Logic 1) were reported by several of the subjects as the more difficult characters. However, some characters with a very low error frequency (e.g., G, V, and Z in Logic 2) were reported as more difficult. This contradiction indicates that the subjects may have been evaluating the difficulty of the character on some criterion other than error frequency. Perhaps they were associating the locatability of the alphabetic character (a design effect) rather than the keying difficulty (a Logic effect). The apparent insensitivity of the subject to error frequency in identifying difficult characters is further shown in the error frequencies of "A" and "B". Whereas these characters have a high relative error frequency for Logics 1, 2, and 3, the subjects using these Logics typically evaluated "A", "B", and also "C" as the easier characters to key-in. This result also supports the possibility of subject sensitivity to keyboard design.

The data for the alphabetic/numeric transitions, while not showing any significant Logic or Replication effect, did show accuracy values consistent with numeric keying accuracy and alphabetic keying accuracy. This result indicates the transitions were not any more difficult than the consecutive numerics or alphabetics, for any of the Logics.

2. LOGIC/KEYBOARD EFFECTS ON KEYING TIME

Numeric keying time, as expected, shows results consistent with the fixed numeric character arrangement across keyboard designs (Logics). Very slight improvement is seen in all Logic conditions, indicating an early or previously learned Logic and design (recall the numeric arrangement is that of the push button telephone). The results reported in this study indicate numeric key stroke times similar to those previously reported for this arrangement. Numeric stroke time on the third Replication averaged approximately 1.0 seconds for the four Logics studied, compared with a key stroke time of .67 seconds reported in Reference 8. One possible explanation for this discrepancy is the level of learning that had been achieved in the two studies. In this research, the data show evidence that learning possibly had not been completed, and therefore, further reduction in keying time could be expected. The level of learning for Conrad's data is unknown, but expected to be high.

Total list keying time vividly presents the superiority of Logic 4, as did total list keying accuracy. The list time for Logic 4 is close to 30% faster than the other Logics, which show virtually no difference among themselves. Significant learning is present in all Logics; therefore. it is uncertain as to the anticipated final relative differences among the Logics. One can reasonably assume, however, that Logic 4 will continue to be superior because of the fewer number of keystrokes to generate an alphabetic character.

One possible source of the Logic effect was identified as the accuracy rate associated with each Logic. The rationale is that more errors will require more corrections and thus take longer to key-in the list. To test this possibility, Calculated List Time (CLTIME) was obtained from the NTIME and ASTIME data for each Logic (these values were derived from the error-free key-ins and thus represent error-free performance). The mean CLTIME for each Logic and Replication is plotted in Figure 28. This plot, when compared with that in Figure 23, shows virtually identical trends and relationships between Logics.

Similarly, as before, a two-way (Logic by Replication) ANOVA shows a significant Logic effect, $F(3,6) = 39.95$, $p < .0002$, and a significant Replication effect, $F(2,6) = 12.17$, $p < .007$. Duncan's Multiple Range Test on the Logics reveals, as before, a significant difference ($\alpha = .05$, df = 6) between Logic 4 and the other three Logics, and no differences among Logics 1, 2, and 3. This result strongly contradicts the possibility that keying accuracy is the source of this effect. Another possible source will be discussed shortly, in conjunction with alphabetic keying time.

From the results presented previously, alphabetic keying time appears to be the primary measure accounting for the observed differences in total list time. As the results indicate, the time to key an alphabetic character with Logic 4 is approximately twice as fast as the time with Logic 1, 2, or 3. This basic time difference is easily accounted for by the differences in Logic structure. Logics 1 and 2 require three key strokes to generate an alphabetic character. Logic 3 requires two or three key strokes. Logic 4 requires only one key stroke.

In order to equalize this difference between Logics, alphabetic stroke time was extracted from the data and noticeably different results are obtained. Logic 1 now is observed to have the fastest stroke time and Logic 4 now has the slowest. Interestingly, this implies the subject is actually keying faster with Logics 1 and 2, but performing worse in the aggregation because more (3 times) strokes are required to generate an equivalent character. Thus, it

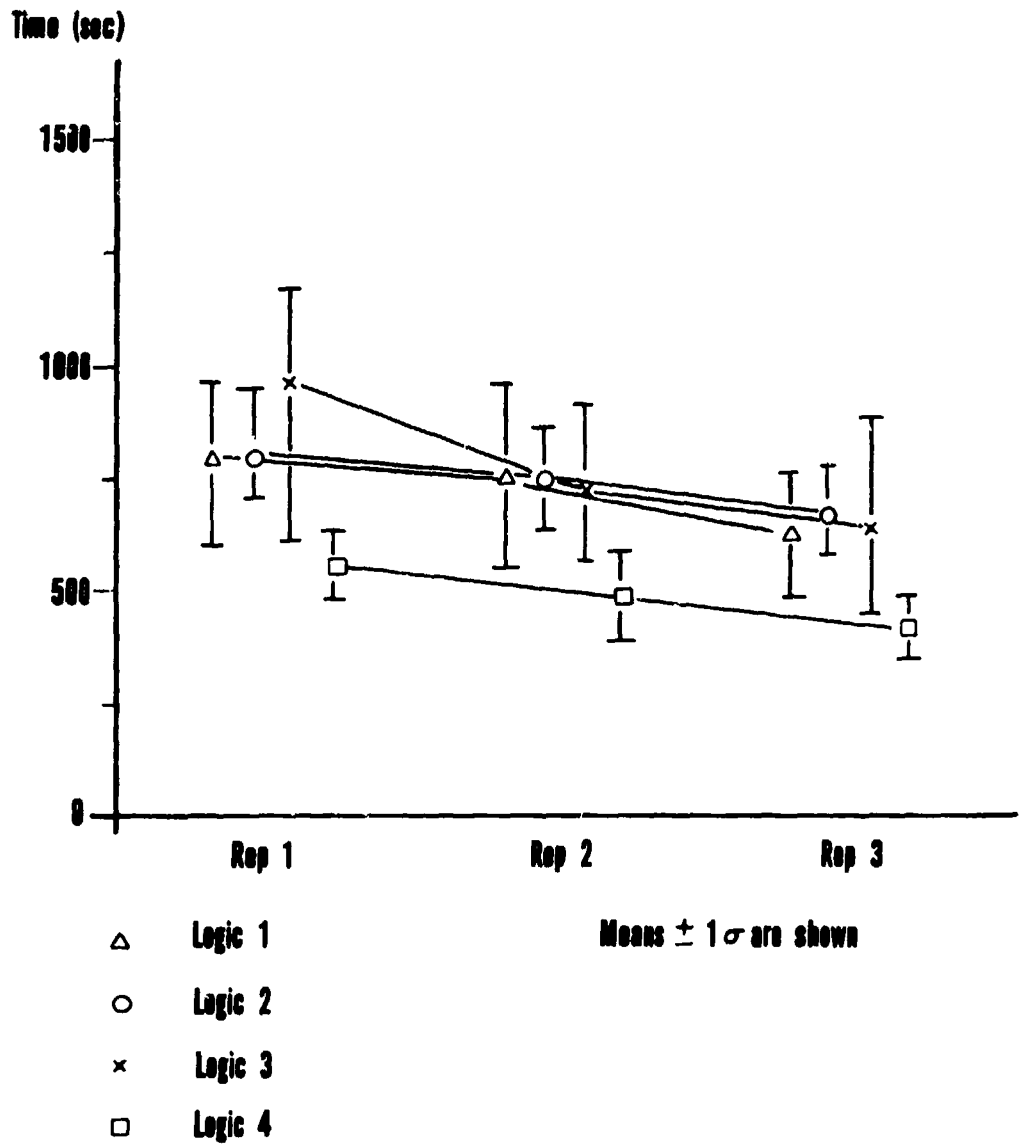


Figure 28. Mean Calculated List Keying Time (Seconds) by Logic and Replication

appears this basic Logic difference is the source of the Logic effect observed in both total list time and alphabetic keying time.

Differences among Logics can also be accounted for using the stimulus-response paradigm (Reference 20). If the keying task used in this research is structured into a discrimination (stimulus input) stage, mediation stage, and response execution stage, Logics 1 and 2 loop through the latter two stages three times before an alphabetic character is generated; Logic 3 loops through two or three times; and Logic 1 only passes through these stages once. Thus, since there is a time factor involved in each of these stages, Logic 4 would obviously be the fastest.

As one further evaluation of the keying time data, methods-time measurement (MTM) tables were consulted (Reference 21) and estimated times derived for a cluster from the data collection list: '2345'. The MTM values were calculated by using tabled values for a reach involving finger motion to a small object requiring accuracy, a contact grasp, and a pressure activation. Based on this approach, MTM predicted a keying time of 2.46 seconds for '2345' using Logic 1. This MTM value is consistent with Conrad's data (predicting a time of 2.68 seconds), and the data from this experiment for Logic 1 of 2.50 seconds for the string '2345'.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions supported by the results of this research will be stated. Subsequently, recommendations regarding an improved keyboard design based on subjects' comments (Appendix B) will be provided, along with recommendations regarding further research.

1. CONCLUSIONS

Of the Logics investigated, one-hand keying of alphanumeric clusters can be accomplished most accurately and fastest with Logic 4 and a suitable keyboard designed for one-hand operation. The data summarized in Table 4 indicate that this Logic is fastest and most accurate when compared to other viable Logics for keying alphanumeric characters. The tabularized data also show the primary difference between Logic 4 and the other three Logics to be time oriented. The time-related dependent variables were all significant, with the exception of numeric keying time which was expected to be non-significant. Further, previously presented data show Logic 4 to be essentially learned from the start of the data collection. The other Logics, most notably Logic 1, not only exhibit a more pronounced learning trend, but also had yet to reach the level of initial performance for Logic 4 (even after three Replications).

Regarding the three Logics which used the same keys for both the alphabetic and numeric characters, Logic 3 which utilized two "ALPHA" keys appears the best performer. However, the apparent reason for Logic 3's superiority is that fewer key strokes are required to generate an alphabetic character.

It also has to be concluded that some additional performance improvement is possible for all Logics, and therefore, performance values for the learned user remains questionable, but is expected to approach those achieved in other referenced studies.

TABLE 4

RESULTS SUMMARY TABLE

		Logic[2] 1	Logic[2] 2	Logic[2] 3	Logic 4	Logic 4 Actual Values	Significant
Numeric	Accuracy	99.5	99.4	100.0	100.0	99.6%	No[3]
	Keying Time	108.6	112.3	120.3	100.0	.971 sec	No
List	Accuracy	99.6	99.9	99.8	100.0	99.7%	No
	Keying Time	156.7	156.5	152.9	100.0	436.863 sec	Yes
Alphabetic	Accuracy	97.2	99.6	98.8	100.0	99.7%	No
	Keying Time	202.8	215.5	197.4	100.0	1.435 sec	Yes
	Stroke Time	67.5	75.9	85.2	100.0	1.435 sec	Yes
A/N Trans.	Accuracy	99.1	97.3	97.3	100.0	99.1%	No
Calculated List Time		148.8	161.7	[illegible]2.1	100.0	442.858 sec	Yes

1. All keying times are for error-free performance with the exception of List Keying Time.

2. Values are expressed as a percentage of Logic 4.

3. Practical significance for Numeric Accuracy, all others refer to statistical significance.

2. DESIGN RECOMMENDATIONS

Logic 4 and a keyboard design comparable to that used in this research are recommended, based on the results observed under the experimental conditions of this research. With regard to the implementation of this Logic, the subjects offered no better alternative and rated Logic 4 "Not Difficult". The keyboard design used with Logic 4 received minor criticism regarding the location of the "Z". To remain consistent with the pattern, the "Z" should probably be placed below the "U".

If space is such a critical factor that a keyboard of this type is impractical, based on the results of this research a design which utilizes Logic 3 but has the layout of the keyboard used with Logic 1 and 2 is recommended. Additionally, a third "ALPHA" key should be added to designate the center alphabetic character. The location of the "ALPHA" keys should also be changed, according to subject opinions. Many subjects felt the "ALPHA" key was visually and tactilely imbedded among the other keys. Subjects recommended either a location or shape change to give prominence to these keys. A recommended keyboard design incorporating these improvements is conceptualized in Figure 29.

3. RESEARCH RECOMMENDATIONS

The results show learning is apparently still occurring after the three Replications used in this research. Based on this observation, further research is recommended which concentrates on subject performances after the data show a fully learned condition. Initially, such a study would be informative for both the superior Logic 4/Keyboard C design of this research, and the recommended Logic/Keyboard design of Figure 29. It would be expected that, with enough learning, key stroke time could be reduced to closely approximate that found by Conrad and others, with accuracy remaining close to the 99.5% correct value found in this research, and by Conrad and others.

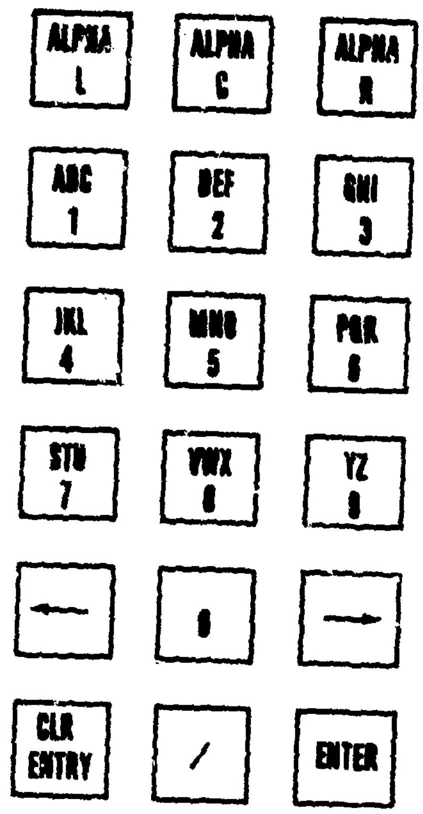


Figure 29. Recommended 4 x 3 Matrix Keyboard Design

Another research recommendation already alluded to is the study of keying accuracy and keying speed performance for the Logic/Keyboard design recommended earlier in this Section. Based on observed performance with Logic 3 and subjective comments regarding the design of Keyboard A (Logic 1 and 2 Keyboard), it is expected that keying performance would be superior to that of Logic 3 and perhaps even approach the keying performance of Logic 4.

Also, further research is recommended which examines performance with the alternative Logics under more realistic experimental conditions. First, the keying task should be supplemented with other realistic tasks to create the divided attention situation under which operation of the keyboard is likely to occur. A tracking task, visual search task, and/or an auditory recognition/verbal response task would be candidate auxiliary tasks representative of typical flight crew tasks. Also, since military pilots fly with gloves on, the effect, if any, gloves have on keying performance needs to be ascertained. Along with these, the subjects should, more properly, be pilots, who are trained to the divided attention nature of commanding an aircraft.

APPENDIX A

INSTRUCTIONS TO SUBJECTS

1. GENERAL INFORMATION

The study in which you are about to participate, examines performance differences associated with various alphanumeric keyboard designs. In the course of your participation today, you will be trained on the use of an alphanumeric keyboard, you will be allowed to practice with the keyboard, and then I will ask you to create a list on the CRT using the keyboard. At this time, I will explain the keyboard you are about to use and the method you must use to get a numeric or alphabetic character. . . .

a. Keyboard A/Logic 1

As you notice, this arrangement is a familiar one. The numbers are arranged in the same location as they are on pushbutton telephones (show location of 1, 2, 3, 4, 5, 6, 7, 8, 9, 0). The alphabet has been assigned to the keys 1 through 9 with three letters on each key. The exception is the last key, which has only the two letters Y and Z. Notice also, there is a left, center, and right position for a letter on the key, thus A is left, B is center, and C is right; Y is left, Z is center, and there is nothing in the right position on this (the 9) key.

Further, for this keyboard, notice there are two inactive keys and six special function keys (show the six). I'll explain these special function keys as we go along.

To select a number, you simply depress the keys 1 through 0, corresponding to the desired number 1, 2, 3, 4, 5, 6, 7, 8, 9, 0 (demonstrate on CRT).

To select a letter, you must depress three keys in sequence. The first key you depress will always be the "ALPHA FUNCTION" key.

The second and third key you depress depends upon which letter you want. If you want a letter on the "5" key, you depress the "5" key second; then if it is specifically the M you want, depress the "4" key third; if it is the N you want, you depress the "5" key third; if it is the O you want, depress the "6" key third. The general method for selecting a letter is to:

1. Depress the "ALPHA FUNCTION".
2. Depress the key which has the letter on it which you want.
3. Depress the left, center, or right key in that row of three keys which corresponds to the left, center, or right position of the desired letter.

I will now demonstrate: 1, 2, 3, BRAVO 4 5 6. Now you create this same string (Subject keys alphabetic/numeric string while experimenter observes).

Are there any questions?

b. Keyboard A/Logic 2

As you notice, this arrangement is a familiar one. The numbers are arranged in the same location as they are on pushbutton telephones (show location of 1, 2, 3, 4, 5, 6, 7, 8, 9, 0). The alphabet has been assigned to the keys 1 through 9 with three letters on each key, the exception is the last key, which has only the two letters Y and Z. Notice, there is a first (or left), second (or center), and third (or right) position for a letter on the key, thus A is first, B is second, and C is third; Y is first, Z is second, and there is nothing in the third position on this key.

Further, for this keyboard, notice there are two inactive keys and six special function keys (show the six). I'll explain these special function keys as we go along.

To select a number, you simply depress the key 1 through 0, corresponding to the desired number 1, 2, 3, 4, 5, 6, 7, 8, 9, 0 (demonstrate on keyboard).

To select a letter, you must depress three keys in sequence. The first key you depress will always be the "ALPHA FUNCTION" key. The second and third key you depress depends upon which letter you want. If you want a letter on the "5" key, you depress the "5" key second; then if it is specifically the M you want, depress the "1" key third; if it is the N you want, you depress the "2" key third; if it is the O you want, depress the "3" key third. The general method for selecting a letter is to:

1. Depress the "ALPHA FUNCTION".
2. Depress the key which has the letter on it which you want.
3. Depress the "1", "2", or "3" key which corresponds to the left, center, or right position of the desired letter.

I will now demonstrate: 1, 2, 3, BRAVO 4 5 6. Now you create this same string (Subject keys alphabetic/numeric string while experimenter observes).

Are there any questions?

c. Keyboard B/Logic 3

As you can see, this arrangement is somewhat unfamiliar. While the numbers are arranged in the same location as they appear on push-button telephones (show location of 1, 2, 3, 4, 5, 6, 7, 8, 9, 0), the letters have been assigned keys 2 through 0, with three letters on each key, the exception is the "4" key which has only the two letters, "A" and "B". Notice, there is a left, center, and right position for a letter on a key. Thus, "A" is in a left position, "B" is in a center position, and there is nothing in the right position on the "4" key.

Further, notice that for this keyboard, there is one inactive key and seven special function keys (show the seven). I'll explain these special function keys as we go along.

To select a number you simply depress the key "1" through "0", corresponding to the desired number 1, 2, 3, 4, 5, 6, 7, 8, 9, 0 (demonstrated on keyboard).

To select a letter, you must depress either two or three keys in sequence, depending upon the letter desired. A letter in the left position requires two keys - the ALPHA LEFT first, followed by the key upon which the desired letter is located (i.e., To select an "A", you first depress ALPHA LEFT and then depress the "4" key). Letters in the right position require a similar action, only the ALPHA RIGHT key is depressed instead of the ALPHA LEFT. (i.e., To select a "K", you first depress ALPHA RIGHT and then depress the "5" key). A letter in the center position requires three keys - the ALPHA LEFT, then the ALPHA RIGHT, then the key upon which the desired character is located (i.e., To select an "M", you first depress ALPHA LEFT, then ALPHA RIGHT, and then the "8" key). The general method, again, is to:

1. Depress either the ALPHA LEFT alone, the ALPHA RIGHT alone, or the ALPHA LEFT followed by the ALPHA RIGHT.
2. Depress the key which has the letter on it which is desired.

I will now demonstrate: 1, 2, 3, BRAVO 4 5 6. Now you create this same string (Subject keys alphabetic/numeric string while experimenter observes).

Are there any questions to this point?

d. Keyboard C/Logic 4

As you can see, this arrangement, while not familiar, is simply a matrix of letters and numbers in sequence. Notice further, that there are seven inactive keys and five special function keys (point out the five). I'll explain their purpose as we go along.

To select a number, you simply depress the key 1 through 0, corresponding to the desired number 1, 2, 3, 4, 5, 6, 7, 8, 9, 0 (demonstrate).

To select a letter, you also simply depress the key A through Z, corresponding to the desired letter A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z (demonstrate). I will now demonstrate: 1, 2, 3, BRAVO 4 5 6. Now you create this same string (Subject keys alphabetic/numeric string while experimenter observes).

Are there any questions to this point?

2. LIST AND DISPLAY INFORMATION

Before you practice, let me explain the list format, display format, and the special function keys.

The list is formatted in three columns, by rows. In other words, you read across the columns a row at a time. As you key-in the letters and numbers, they will appear below the dashed line, starting where the cursor is now located and proceeding left to right. This "Scratch Pad" portion of the CRT is made up of three lines, one for each of the columned clusters in the row you are keying-in. You key the row into the Scratch Pad in the following manner: ABC/12335, point out errors, back space, correct to 12345, forward space,/XYZ. When you've completed a row from the list, depress ENTER, which clears the scratch pad, and returns the cursor to the starting point for the next row. Notice that the "/" gets used after the first two lines in the Scratch Pad and the ENTER gets used only after the third line when you are ready to clear the Scratch Pad and start the next row on the list. Also, to re-emphasize, errors can only be corrected while in the Scratch Pad, and only while you are in the same line. Once you've gone on to the next Scratch Pad line, or entered the Scratch Pad lines, you can not go back and correct.

I've demonstrated the keyboard and the method for keying-in letters and numbers in the Scratch Pad, I've demonstrated the special functions for back-spacing, forward-spacing, clearing an entry, and entering.

Are there any questions now, before you practice?

3. PRACTICE INSTRUCTIONS

This is the list for you to practice with. After you key-in all the rows of the list, continue by simply starting over at the top of the list. Your practice will continue until you have keyed-in the list twice in a row, without making an error (After subject completes practice session, allow a 5-10 minute break before proceeding to the data collection session).

4. DATA COLLECTION INSTRUCTIONS

Here is the list I would now like you to key-in using this keyboard. Remember, accuracy counts as well as speed. Therefore, key-in this list at a comfortable pace, making sure that the lines in the Scratch Pad are error-free before they are entered. I will ask you to key-in this list three times, however, wait for my instruction each time through the list. Do you have any questions at this time? You may proceed when you are ready.

APPENDIX B

KEYBOARD/LOGIC QUESTIONNAIRE

and

SUMMARY OF RESULTS

TABLE OF CONTENTS

KEYBOARD/LOGIC QUESTIONNAIRE

1. Did you make any errors? How Many?

   Rep 1 _____ _______

   Rep 2 _____ _______

   Rep 3 _____ _______

2. Did you correct all errors? Estimated Accuracy

   Rep 1 _______ _______

   Rep 2 _______ _______

   Rep 3 _______ _______

3. This method of keying-in letters and numbers is

Not Difficult		Moderately Difficult		Very Difficult
☐	☐	☐	☐	☐

4a. Where any characters more difficult to key-in than the others?

Which ones?

4b. Where any characters easier to key-in than others?

Which ones?

5a. Were any clusters more difficult to key-in than any others?

Which ones?

5b. Were any clusters easier to key-in than others?

Which ones?

6. Do you have a pushbutton telephone?

Summary of Subjects' Comments for Logic 1

Method was:

Not Difficult		Moderately Difficult		Very Difficult
2	1	3	1	

Easier Characters:
- Letters requiring same key; e.g., A,N,R, etc.
- Alphabet extremes

Harder Characters:
- Q,U,Z,G,H
- None
- All letters

Easier Clusters:
- FL, ABC, TWINE, HUDQLS, MUPPY, JUVTY
- Number strings

Harder Clusters:
- CXQCK, HRMZ
- Coordinates
- None

Comments:
- Alpha key imbedded, prefer relocation
- Prefer to have "Alpha Hold" to key consecutive letters without having to key ALPHA each time
- Relocate special functions above 4 x 3 matrix
- Prefer less key-hits per letter

Summary of Subjects' Comments for Logic 2

Method was:

Not Difficult		Moderately Difficult		Very Difficult
	4	2	1	

Easier Characters:
- None
- Letters requiring same key-hit; e.g. A,E,I
- 1,2,3

Harder Characters:
- Z,D,G,Q,V
- None

Easier Clusters: FL, TWINE, FOXX, ABC

Harder Clusters:
- CXQCK, HRMZ
- Number strings
- Ones unpronouncable
- Coordinates

Comments:
- Relocate ALPHA key, or shape code
- Three key-hits per letter too many, 2 might be acceptable
- Logic was not difficult to learn
- Key for each letter would be faster

Summary of Subjects' Comments for Logic 3

Method was:

Not Difficult		Moderately Difficult		Very Difficult
1	3	2		1

Easier Characters:
- F,L,A,Z
- Letters in easy key positions
- Vowels
- Numerics

Harder Characters:
- Q,X,B,N,S,E,W,Z
- Letters not used very much
- Letters in middle of subsets

Easier Clusters:
- ABC, TWINE
- Coordinates
- 12345
- Repeated Clusters (e.g., FL)

Harder Clusters:
- HUQLS, CXQCK, HRMZ, VGJ, JUVTY
- Non-phonetics

Comments:
- Relocate ALPHA keys
- Shape code ALPHA keys
- Add key for ALPHA Center
- Separate backspace and forward space from ALPHAs

Summary of Subjects' Comments for Logic 4

Method was:

Not Difficult		Moderately Difficult		Very Difficult
3	3		1	

Easier Characters: - A,Z,B,C

- Numbers

Harder Characters: - Z,J,V,W,X,F,G

Easier Clusters: - ABC, 123, ABZ, ABQ, FL, MUPPY

- Phonetics
- Number strings

Harder Clusters: - Latitudes/Longitudes

- Ones unpronouncable
- HUQLS, CXQCK, VGJ, RGS

Comments: - More space separation between alphabetics and numerics

- "Z" out of place; put under the "U"
- Forward space imbedded
- Method difficult because familiar with "QWERTY" arrangement.
- Key pressure caused fatigue after long list

APPENDIX C

CLUSTER AND CHARACTER ERROR HISTOGRAMS

TABLE OF CONTENTS

	TOTAL (124)		REP 1 (43)	REP 2 (42)	REP 3 (37)
N374518 W642309	XX	2	X	X	
2345					
678					
RXI					
10967					
432					
ABC					
13890	XX	2	X	X	
510					
B310 D67	XXXXXX	6	XXXX	X	X
FL200					
333	X	1			X
JUVTT					
FL222	XX	2	X	X	
196	XX	2	X	X	
VGJ					
FL218					
175					
S440525 W493732	X	1		X	
FL344	X	1		X	
197	X	1		X	
POLX	XXX	3		X	XX
FL438	X	1			X
604					
CRQCK	XXX	3	X		XX
50689					
567					
ARQ	XX	2		XX	
FLA95	XXX	3	X	X	X
495	X	1	X		
B164 D88	XXX	3	X	XX	
37890					
421	X	1	X		
BGS	XX	2			XX
69877	XXX	3	X	XX	
637					
TWINE	XXX	3	X	XX	
FL400	XX	2	X		X
510	X	1		X	
ABZ	XXXX	4	X	X	XX
FL328	XXX	3	X	X	X
483					
B299 D157	XXX	3	X	XX	
61945	XXX	3		XX	X
278					
HUMZ	XXX	3	XX		X
27845					
619					
N251908 W062847	XXXX	4	X	X	XX
FLA83	X	1	X		
328					
HUQLS	XXX	3	X		XX
FL510	X	1		X	
200					
JGV	XXXX	4	XX	XX	
63777					
698	XX	2	X		X
HOPF	XX	2		X	X
42190	XXX	3	X		XX
378					
BMG	X	1	X		
FLA95	X	1	X		
495	X	1			X
MUPPY	XX	2		X	X
56789					
506					
JUVTT	XXX	3	X	X	X
FL604	XXXX	4	X	X	XX
438	XX	2		X	X
LOK	X	1			X
FL197	X	1	X		
344	XXX	3	X		XX
S310758 E012345	X	1		X	
FL175	X	1			X
218	X	1			X
POXX	XX	2	XX		
FL196	XX	2		X	X
222	X	1		X	
RCI					
FL333	XX	2	X	X	
200	X	1	X		
ABC	XXXX	4	XX	X	X
51090					
158					
B667 D899	XX	2	X	X	
43267	X	1		X	
109					
TWINE	XXX	3	XX	X	
o7845					
203	XX	2	XX		

Error Frequency by Cluster (Logic 1)

	TOTAL (69)		REP 1 (28)	REP 2 (20)	REP 3 (21)
N374518 W642309	X	1	X		
2345					
673					
R21	[illegible]	1		X	
10957					
432					
ABC	XXX	3		XX	X
15890					
510	X	1			X
B310 D67	X	1		X	
FL200	X	1	X		
333					
JU'TY	XX	2	X		X
FL222	X	1			X
196					
W'					
FL718					
175	XX	2			XX
SA40525 BA93732	XXX	3	XX	X	
FL344					
197					
POLK					
FL458					
604					
CHQCK	X	1	X		
50689					
567					
ABQ	XXX	3	XX		X
FLA95					
495	XXX	3	X	X	X
B166 D88	XX	2	X		X
37890	X	1			X
421					
RGS					
69877	XX	2	X		X
637	X	1		X	
TWINK	X	1			X
FL200					
510					
ABZ					
FL328	X	1	X		
483	X	1		X	
B299 D157	XXX	3	X		XX
61945	X	1		X	
278					
WRNZ					
27845					
619	X	1	X		
N251908 W062847	XXXX	4	XX	XX	
FL483	XXXX	4	XX		XX
328					
MUQLS					
FL510	XX	2		XX	
200					
JGV					
63777					
698	XX	2	X		X
HOFF	XX	2	XX		
42190					
378					
EMG					
FL495	XX	2	X	X	
495					
MUPPY					
56789					
506					
JUVTY					
FL604	X	1			X
458					
LO'.	XX	2	XX		
FL197	X	1		X	
344					
S310758 E012345					
FL175					
218					
FOXX	X	1	X		
FL196					
222					
RC1					
FL333	X	1		X	
200	X	1			X
ABC	XXXXX	5	XX	XX	[illegible]
51090					
158					
B667 D899	XXXX	4	X	XX	X
43267					
109					
TWINK					
67845					
203					

Error Frequency by Cluster (Logic 2)

	TOTAL (86)		REP 1 (27)	REP 2 (35)	REP 3 (24)
N374518 W042309	X	1		X	
2345					
678					
R31	X	1	X		
10967					
432					
ABC	XX	2		X	X
15890	X	1			X
510					
B310 D67	XXX	3		XX	X
FL200					
333	XX	2	X	X	
JUVTY	XXX	3		X	XX
FL222					
196	X	1		X	
VGJ	XXXXX	5	XX	X	XX
FL218	XX	2	X		X
175					
S440525 W093732	XXX	3		XX	X
FL344					
197					
POLK					
FL458	XX	2			XX
604					
CIQCK	XX	2	XX		
50689	X	1		X	
567					
ABN	X	1		X	
FL495					
495					
B166 D88					
37890	X	1			X
421					
BGS					
69877	X	1		X	
637					
TWINE	X	1	X		
FL200					
510	X	1			X
ABZ	XXXXX	5	XX	XX	X
FL328	X	1		X	
483					
B299 D157	XXXXXX	6	XXX	X	XX
61945					
278					
HHHX	XXX	3		XX	X
27845	XX	2		X	X
619					
N251908 W062847	XX	2		XX	
FL483					
328					
NUQLS					
FL510	XX	2		XX	
200					
JGV					
63777	X	1		X	
698	X	1			X
NOFF	XX	2	XX		
42190	XX	2	X	X	
378	X	1	X		
ENG	XXX	3	XX	X	
FL495					
495					
MUPPY	XX	2	X		X
56789					
506					
JUVTY	X	1	X		
FL604	XX	2		X	X
458					
LOK	X	1	X		
FL197	X	1		X	
344					
S310758 E012355	X	1		X	
FL175	X	1		X	
218	X	1	X		
FOXX	XX	2		X	X
FL196					
222					
RCI					
FL333	XX	2	X	X	
200	X	1	X		
ABC	XXX	3	X	X	X
51090					
158					
B667 D899	XX	2	X	X	
43267					
109					
TWINE	X	1		X	
67845					
203					

Error Frequency by Cluster (Logic 3)

	TOTAL (47)		REP 1 (15)	REP 2 (14)	REP 3 (10)
B3745'8 W642309	X	1			X
2345					
678					
RZJ					
10967					
432					
ABC					
15890					
510					
B310 D67					
FL200					
333					
JUVTT	XX	2		X	X
FL222					
196					
VGJ					
FL218					
175					
B440525 B493732	XX	2			\X
FL344					
197	X	1	X		
FOLE					
FL458					
604	X	1	X		
CXQCK					
50689					
567					
ABQ					
FLA95	X	1			X
495					
B166 D88	XX	2		X	X
37890	X	1		X	
421					
BGJ					
69877					
637	X	1	X		
TWINE	X	1	X		
FL200	X	1			X
510					
ABZ					
FL328	X	1	X		
483	X	1	X		
B299 D137					
61945					
278					
WMKX					
27845					
619					
H251908 W062847	XXX	3	X	XX	
FLA83	XX	2	XX		
328					
KUQLS					
FL510	X	1			X
200					
JGV					
63777	X	1		X	
698					
HOFF					
42190					
378					
EMG					
FLA95	X	1	X		
495	X	1		X	
MUPPY					
56789					
506					
JUVTT	XXXX	4	XX	X	X
FL604					
458	XX	2		X	X
LOK					
FL197	XXXX	4		X	XXX
344					
S310758 B012345	XX	2		X	X
FL175	X	1			X
218	XX	2	X		X
FOXX					
FL196	X	1		X	
222					
RC1					
FL333					
200	X	1	X		
ABC					
51090					
158					
B667 D899	XXXX	4	X	X	XX
43267					
109					
TWINE					
67845					
203	X	1		X	

Error Frequency by Cluster (Logic 4)

	TOTAL (121)		REP 1 (44)	REP 2 (41)	REP 3 (36)
A	XXXXXXXX	8	XXX	XXX	XX
B	XXXXXX	6	X	XXXX	X
C	X	1			X
D	XXXXXXXX	8	XXXXX	XX	X
E					
F	XXXXXXXX	8	XXXXX	X	XX
G	XXXXX	5	XX	X	XX
H					
I	X	1	X		
J					
K	XX	2			XX
L	XXXXXXX	7	XX	X	XXXX
M	XX	[illegible]	XX		
N					
O	XX	2		X	X
P					
Q	XXXXX	5	XX	X	XX
R	X	1	X		
S	X	1		X	
T	XXXXX	5	XXX	XX	
U	XX	2		X	X
V	XX	2	X	X	
W	X	1	X		
X	X	1	X		
Y	X	1			X
Z	XX	2			XX
0	XXXX	4	X	XX	X
1					
2	XXXXXX	6	X	XXXX	X
3	XXXXXXX	7	XXX	X	XXX
4	XXXXXXX	7	X	XXXXX	X
5	XX	2		X	X
6	XXXXXX	6		XXXXX	X
7					
8	XXXXXX	6	XX	XX	XX
9	XXXXXXXXXXXX	12	XXXXXX	XX	XXXX

Error Frequency by Alphanumeric Character (Logic 1)

	TOTAL (70)		REP 1 (28)	REP 2 (21)	REP 3 (21)
A	XXXXXX	6	XXX	XX	X
B	XXXXXXXXX	9	XXX	XXX	XXX
C	X	1		X	
D	XXX	3	X	X	X
E					
F	XXXXXXXXX	9	XXXX	XXXX	X
G					
H					
I					
J	X	1	X		
K	X	1	X		
L	XX	2	X	X	
M					
N					
O	XX	2	XX		
P					
Q	XXX	3	XX		X
R	X	1		X	
S					
T					
U					
V					
W	X	1		X	
X	X	1	X		
Y	X	1			X
Z					
0	XXX	3	X		XX
1					
2	XXX	3		X	XX
3	XXX	3	X		XX
4	XX	2	X	X	
5	X	1		X	
6					
7	XXXXX	5		XX	XXX
8	XX	2		X	X
9	XXXXXXXXXX	10	XXXXXX	X	XXX

Error Frequency by Alphanumeric Character (Logic 2)

	TOTAL (76)		REP 1 (20)	REP 2 (32)	REP 3 (24)
A	XXXXXXX	7		XXX	XXXX
B	XXXXXX	6	XX	X	XXX
C	X	1	X		
D	XXX	3		XX	X
E	XXXXX	5	XX	XXX	
F	X	1	X		
G					
H					
I	X	1	X		
J	XXXXXX	6	XX	X	XXX
K	X	1	X		
L	XXX	3	X	XX	
M	XX	2			XX
N	X	1		X	
O	XX	2	X		X
P	X	1	X		
Q	X	1	X		
R	X	1			X
S					
T					
U					
V	XXX	3	X	X	X
W	X	1	X		
X	XX	2		XX	
Y					
Z	XXXX	4	XX	XX	
0	XX	2	X	X	
1					
2	XXXX	4		XXX	X
3	XXXXX	5	X	XXXX	
4	X	1			X
5	XXX	3		XX	X
6	X	1			X
7	XX	2		X	X
8	XXX	3		X	XX
9	XXX	3		XX	X

Error Frequency by Alphanumeric Character (Logic 3)

	TOTAL (47)		REP 1 (17)	REP 2 (13)	REP 3 (17)
A					
B					
C					
D	X	1		X	
E	X	1	X		
F					
G					
H					
I					
J					
K					
L	X	1			X
M					
N					
O					
P					
Q					
R					
S					
T					
U	X	1	X		
V					
W					
X					
Y					
Z					
0	XXX	3	XX		X
1	XXXX	4		XXX	X
2	XXXXXX	6		XX	XXXX
3	XXX	3	X	XX	
4	XXXX	4	XX	X	X
5	XXX	3		X	XX
6	XXXXXX	6	XXX	X	XX
7	XXX	3	X		XX
8	XXXXXX	6	XXX	X	XX
9	XXXXX	5	XXX	X	X

Error Frequency by Alphanumeric Character (Logic 4)

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