A Minimum Chord Stenograph Keyboard For Blind And Sighted Users

by
Zhongzhi Hu

B.A.Sc., Beijing Institute of Technology

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS OF THE DEGREE OF
MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES
DEPARTMENT OF ELECTRICAL ENGINEERING

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
1992

Abstract

This thesis deals with the design and testing of an experimental stenograph keyboard for blind and sighted users. The new keyboard, called the Minimum Chord Stenograph (MCS), is presented. It comprises two panels of six keys, one for each hand. Relocation of the fingers above the keys is at a minimum. A coding scheme for MCS was developed to allow exact phonemic description of the text or speech to be entered by alternate hand typing.

Experiments were carried out with the MCS and with the standard Stenograph-Boswell keyboards. The time between successive movements of hands on the keyboards was precisely measured live with a 386 computer and the statistics have been compiled and analyzed. The results show that the MCS' performance (WPM) is significantly better than the standard stenograph-Boswell; the problem of training time for the stenograph seems to be solved at least at the level of initial competence. Extrapolating from the published results for QWERTY, MCS has much better performance than QWERTY at the initial stage. In conclusion, MCS keyboard may provide an efficient alternative to the existing standard stenograph keyboard and to the QWERTY keyboard.

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

(Signature) ______________________

Department of Electrical Engineering

The University of British Columbia
Vancouver, Canada

Date May 5, 1992

Table of Contents

List of Figures

List of Tables

Acknowledgment

I would like to thank my supervisor, Dr. M. P. Beddoes, for his many fruitful discussions and helpful suggestions, as well as for his invaluable assistance in preparing the thesis.

I am indebted to Dr. P. Graf of Psychology of UBC for his helpful discussions and assistance, N. Newell and T. Markoc for their assistance with some software implementation, and 13 subjects for their cooperation.

Thanks are also due to Drs. C. A. Laszlo and G. F. Schrack for their careful reading and correction of this thesis.

Special thanks are given to my wife, Lei Jin, for encouragement and understanding throughout my graduate study.

I would wish to acknowledge also financial and equipment support from the following organizations:

a. Financial support:
   Operating grant 553462 from the Science Council of British Columbia; and
   Operating grant 583290 from the National Science and Engineering Council of Canada;
b. Equipment support:
   8 Boswell keyboards from the Boswell International Technologies Ltd., Vancouver, British Columbia.

Chapter 1 Introduction

Stenotype machines are the fastest means for encoding verbal information into print or speech. Systems have been developed for the British Palantype and the American Stenograph, and these have been operated at real speech rates by skilled stenotypists. However these kinds of machines are difficult to learn and operate. This thesis deals with the design of and testing of an experimental stenograph keyboard for blind and sighted users. Our objective is to overcome the problems with existing stenograph keyboards and design a new keyboard, which is fast and easier to learn and operate. The new keyboard layout is called the Minimum Chord Stenograph (MCS). Relocation of the fingers above the keys is at a minimum; phonemes are the input quantity. A suboptimum coding scheme for MCS ensures that the maximum information input rate can be reached. The experiments show that less time is needed to learn the keyboard than needed for the standard stenograph-Boswell keyboard and it is faster than Boswell and QWERTY keyboards.

In the next two sections, some background and applications of the stenotype machines are described; and in the last section, the thesis outline is presented.

1.1 Background

Some recent developments in communication aids for the speech impaired have featured synthetic speech output [1]. Like most communication aids, however, they suffer from the problem of data rate restriction, where information transfer is much slower than between able-bodied persons. Typical conversational speech rates are between 150 and 250 words per minute, whereas a good typist can only encode at 60 to 80 words per minute. A dexterous person can therefore communicate via a conventional typewriter keyboard at only about one third the rate of normal speech. Synthetic speech output may be derived from typed information, but conversation by this means is restricted by the low typing rate. A number of systems have been developed to improve the effective typing rate, e.g. ergonomic keyboards, stored word lists [2], etc., but none have achieved sufficient improvement to allow unrestricted conversation at normal rates.

Nevertheless, a mechanical keyboard method for encoding verbatim speech has existed for many years — the stenotype shorthand machine. Stenotype keyboard systems are phonetically based. A spoken word is analyzed into its constituent syllables. Each syllable is then typed, with a coded quasi-phonetic spelling, in one stroke (called a “chord”). This allows a significant speed advantage over conventional QWERTY keyboard operation, hence a trained stenotypist can type verbatim speech at speech rates. A trained stenotypist can therefore record speech via these keyboards without restriction of either speed or vocabulary.

1.2 Applications

Stenotype keyboards were first [3] employed for rehabilitation purposes in January 1977, when Jack Ashely, a British Member of Parliament, began monitoring debates on a real-time speech captioner. This device takes input from a Palantype keyboard, which is operated by a professional stenotypist. The captioner displays output on a visual monitor as a sequence of phonetic syllables, abbreviations, and words; the task of deciphering the meaning of the display is placed on the deaf user.

On broadcast television, real-time captioning for the hearing impaired came three years later; the BBC introduced it in January 1980 for President Reagan's inaugural address [4]. In late 1982, the American network ABC began a similar service, using stenotyped input, for its "World News Tonight" [5]. In both America and Britain, television stations aim at providing high quality orthographic output, with a minimum of lapse into phonetics. In 1991 at the conference on "Technology and Persons with Disabilities" [6], the author witnessed a deaf person reading the audiences' questions by a real time speech captioner similar to Ashely's device. Therefore, with stenotype keyboards, the following applications can be explored:

1. A speech captioning device for some adventitiously deafened persons [7, 8, 9]. This device will be operated by a stenotypist, producing output of phonetically spelled syllables for visual display; it could either be dedicated to a single individual, or employed at gatherings of the deaf.
2. A voice output communication aid for some speech impaired persons [10]. This device is operated directly by the disabled person, and interfaces to a speech synthesizer with a voice output; it could be used, for example, to allow adventitiously deafened individuals to generate their part of a telephone conversation.
3. A speech file editor for some blind persons [11, 12, 13]. This device will be operated by the blind person, permitting the creation, storage, retrieval, editing and output of 'speech files', either as synthesized voice or as hard copy.

1.3 Thesis Outline

A review of past and continuing research in the various keyboards is presented in Chapter 2. Chapter 3 presents a detailed description of our experimental keyboards. In Chapter 4 the typing experiment and testing results are presented and discussed. The final chapter, Chapter

5, summarizes the results of Chapter 3 and 4, and presents appropriate conclusions and recommendations.

Chapter 2 A Review of the Various Keyboards

Keyboards have been widely used and extensively studied as data entry devices in various man-machine communication systems. The typewriter employs a single-press keyboard with letters and numbers (alphanumeric). The standard keyboard is called QWERTY because of the keys in the top row of letters. Multi-press or "chord" keyboards have been employed on manual mail-sorting machines and on "stenotype" machines[14]. Stenotype machines are shorthand typing keyboards which enable a trained stenotypist to record words at natural speaking rates. Most stenotype systems employ phonemic and syllable coding methods, and represent unique means by which speech-like data may be typed in machine-compatible form in real time. Because of their phonemic coding structure, they are also infinite vocabulary devices. It is therefore possible to control a phoneme-driven speech synthesizer, at natural speech rates, from such a stenotype keyboard.

This chapter will review the developments principally in keyboard layout as it affects fast recording from speech. In the next two sections, typewriter keyboards and chord keyboards are briefly reviewed, and finally some discussions are presented in section 4.

2.1 Typewriter Keyboards

The QWERTY keyboard (Figure 1) has monopolized the market for alphanumeric sequential keyboards since its conception over a century ago.

Within two decades, numerous suggestions have been proposed for alternative keyboard arrangements designed to facilitate higher speeds and greater accuracy. However, none of these alternative arrangements has succeeded in replacing the QWERTY keyboard as the standard. The only serious contender that has been widely tested is the Dvorak Simplified Keyboard (Figure 2), developed by August Dvorak and colleagues at the University of Washington in the early 30s ([15, 16]). The Dvorak arrangement featured a number of advantages over the QWERTY system, including a larger home-row vocabulary (3000 vs. 100 common words), greater utilization of right hand keying, more balanced utilization of all fingers of each hand, greater utilization of alternative hand sequences, and minimization of awkward fingering sequences. Large-scale testing of the Dvorak and QWERTY systems [17] revealed that the Dvorak keyboard could be learned in about one-third the time needed to master the QWERTY, and offered additional advantages of greater accuracy (approximately half as many errors), higher speeds (about 15–20%), and reduced fatigue.

Since Dvorak's time, the approach towards designing a new sequential keyboard has become more complex and scientific. This is demonstrated by Griffith (1949, [18]). Griffith analyzed statistically a representative sample of 100,000 words in order to devise the Minimotion Keyboard. Many people still proposed reformed keyboards in the 1970s: for example, the Alphameric [19], the Kroemer[20], the Ferguson and Duncan [21], and the PCD Maltron [22] keyboards. Another possible keyboard arrangement is an alphabetical sequence A to Z.

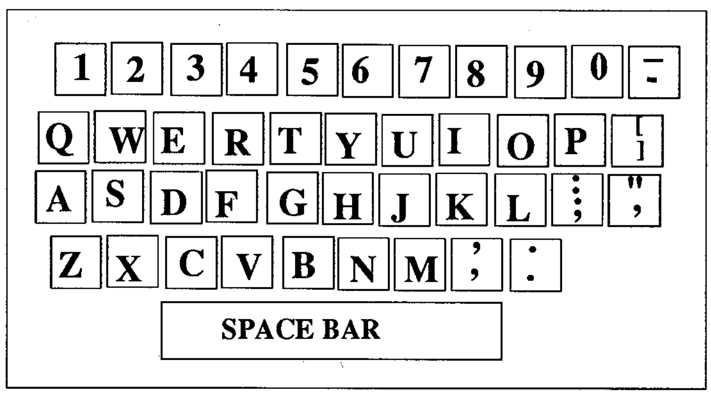

Figure 1 The QWERTY Keyboard

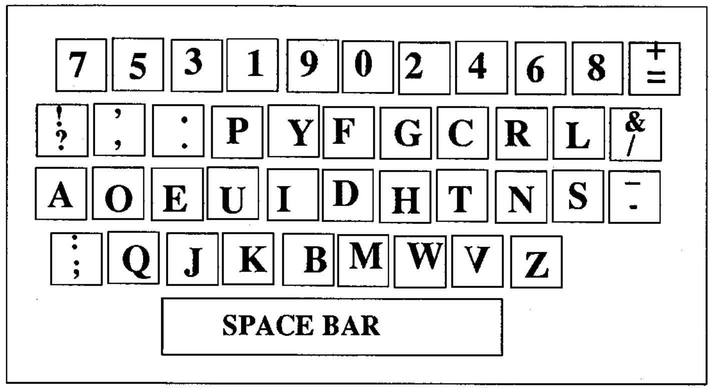

Figure 2 The Dvorak Keyboard

Thus although there has been some dissatisfaction with certain features of typewriter keyboard design, it has apparently proved to be remarkably difficult to demonstrate that the original hundred-year-old concept could be substantially changed to any advantage. Those who have tried have been concerned with two design questions.

1. Can the present number of keys be advantageously rearranged spatially?
2. Can the number of keys be reduced?

The main attack on QWERTY layout came from Dvorak et al. who proposed the Simplified keyboard in which the keys were rearranged so as to bring more work on to the middle row and a more equitable distribution of work between the eight fingers. Extensive trials of the Simplified keyboard have been carried out [23], but no comprehensive account of a controlled experiment has been published, and assessment of its value is not possible.

The main impetus for attempts to reduce the number of keys stems from the generally accepted fact that it is difficult to make hand movements quickly and accurately without visual guidance. It can be argued that a finger movement which involved merely pressure would be easier to make than one requiring movement in the horizontal plane as well as pressure. If reaches are to be eliminated, then clearly no more than ten main keys are available. This means that alphabetic characters may require chords rather than single key strokes.

2.2 Chord Keyboards

Unlike the typewriter keyboards, typing on a chord keyboard is carried out by simultaneous pressing one or more keys. This results in fewer keys being needed on a chord keyboard when compared with the QWERTY keyboard, where keys are pressed one at a time. Several new chord keyboards seem to promise short training time as well as improved performance in other respects.

2.2.1 Stenotype Keyboards

Systems have been developed for the British Palantype and American Stenograph keyboards [24, 25], and these have been operated at 200 to 250 WPM by skilled stenotypists. The layouts of these two English language phonetic keyboards are shown in Figure 3 and Figure 4. Shown in Figure 5 is the Boswell keyboard which was evolved from Stenograph and is being developed in Vancouver [6]. It uses much the same layout as Stenograph, except there is one more vowel key in the center part.

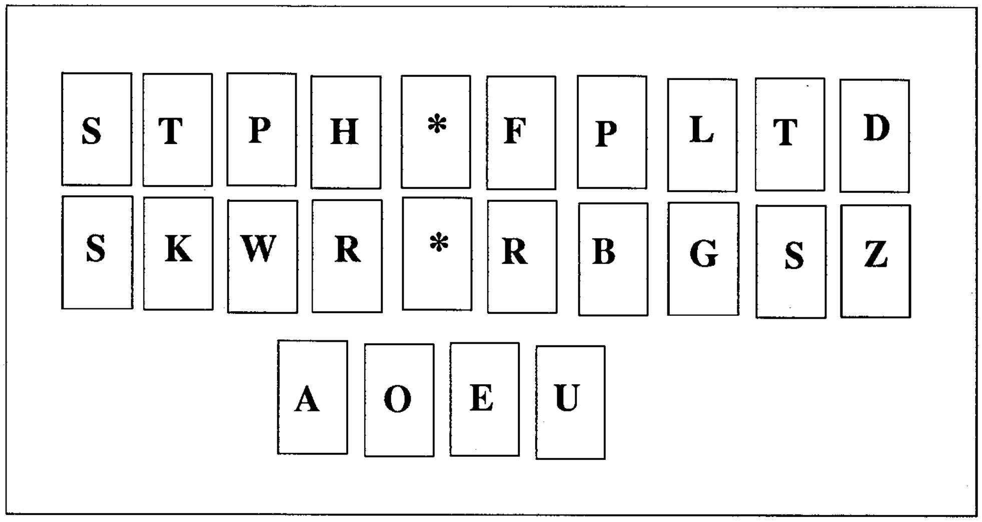

Figure 3 Stenograph Keyboard

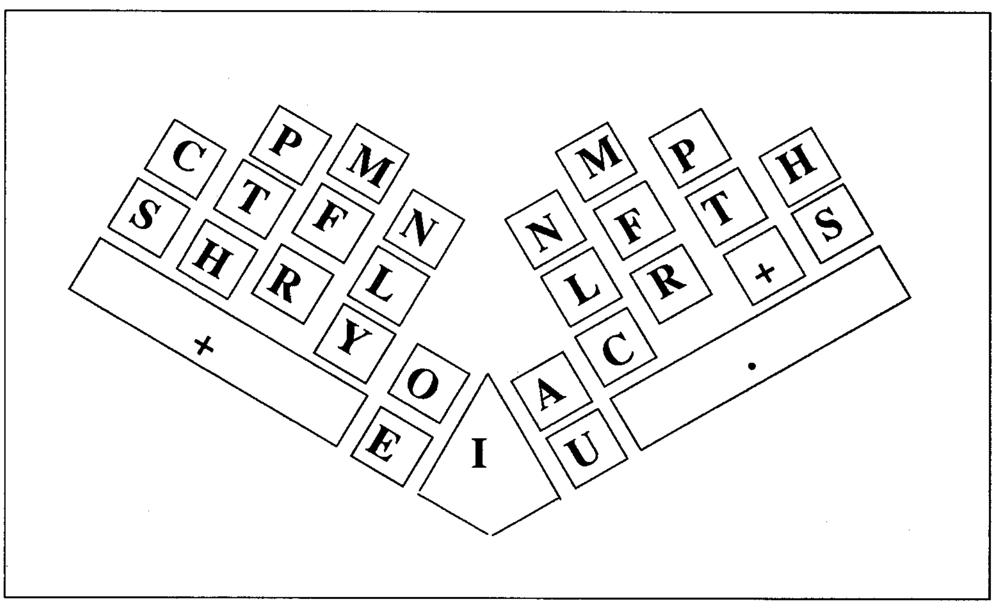

Figure 4 Palantype Keyboard

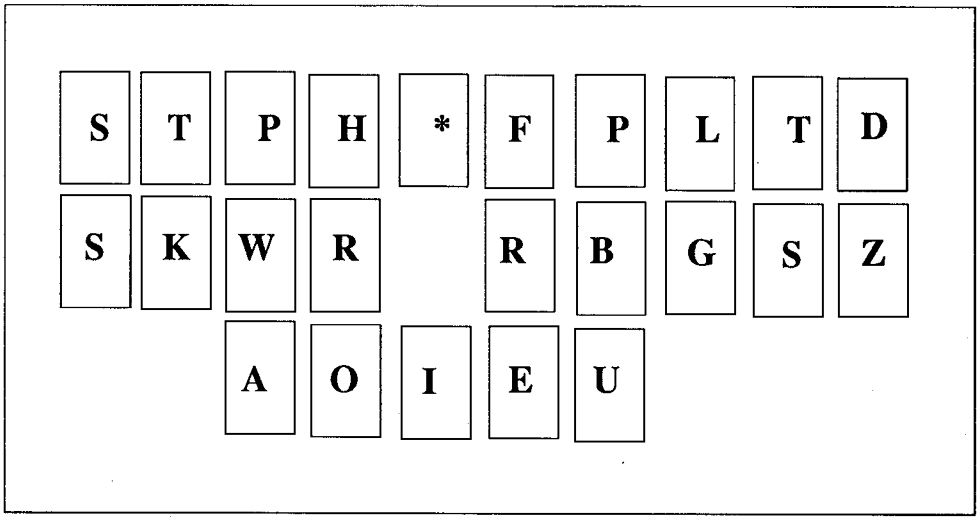

Figure 5 Boswell Keyboard

The keyboards in Figures 3, 4 and 5 all have (a) a left-hand group of initial consonants, (b) a central group of vowel keys, and (c) a right-hand group of final consonants. The basic input unit is a syllable. The syllable consists of a left-hand consonant, or a cluster of consonants, a vowel and a right-hand consonant, or a cluster of consonants. The stenotype machines convert not letters but phonemes represented by keys into text. A skilled stenotypist would record spoken information on such a keyboard by

1. segmenting each word into constituent syllables,
2. spelling phonetically each syllable,
3. encoding this phonetic spelling for the keys available on the keyboard, and

4. typing the syllable in one multi-key stroke of the keyboard.

The above sequence of steps corresponds to Full Phonemic mode, FP. FP is useful in generating synthetic speech and rates can be quite fast. In order to input at top speed, abbreviations must be substituted for the words and even phrases at the level of step 1 and step 2. The number of keystrokes is much reduced and this mode of operation is known as True Courtroom mode, TC. TC is not considered in this thesis.

Experiments carried out recently by Boswell International Technologies give the following rates for FP mode:

Table 1 Performance Data for Boswell in FP Mode

Subjects	Total Training (Hour)	5 min Test (WPM)	Characteritic
D	744	62	Sighted, Dyslexic
L	508	60	Sighted, Normal
M	261	34	Blind
P	287	54	Blind
R	111	34	Sighted, Normal

The subjects D and L were found to be able to type effectively. Blind subject M was methodical but slow; blind subject P was reasonably fast and accurate. The figures in the above table confirm the long training time needed.

2.2.2 Chord Keyboards

Klemmer (1958, [26]) of IBM studied a 10–key chord keyboard with 5 keys arranged in a semi-circle for each hand. He allotted the most frequently occurring letters in the English language to single keys, while other characters were represented by depressing 2 of the 10 keys. Klemmer trained two subjects on his keyboard, one of whom was a skilled typist. He found that after 40 h of training, the typist had reached a speed of 47 WPM with 0.3% error rate, compared with 29 WPM and 0.7% errors for the naive typist. It was concluded that the learning curves for the acquisition of chord typing were comparable with those expected on a QWERTY typewriter. In 1959, Lockhead and Klemmer of IBM (1959, [27]) carried an evaluation of an 8–key chord-typewriter. This chord keyboard consisted of two arcs of four keys, and the thumbs were not used. Four subjects learned the 137 chord patterns in less than 30 h. Lockhead and Klemmer concluded that " the ability of people to learn and their willingness to use multiple key patterns is encouraging".

Gopher and Raij (1988, [28]) developed a two-hand chord keyboard (Figure 6) for the Hebrew language. This keyboard is comprised of two separate panels, one for each hand, with 5 keys on each panel. 22 Hebrew letters were mapped onto key combinations such that the more frequently used letters were associated with easier chords. The two panels are tilted to an upright position and the panels face each other so that there is always a match between the fingers used to type the same characters on both panels and the patterns of pressed keys.

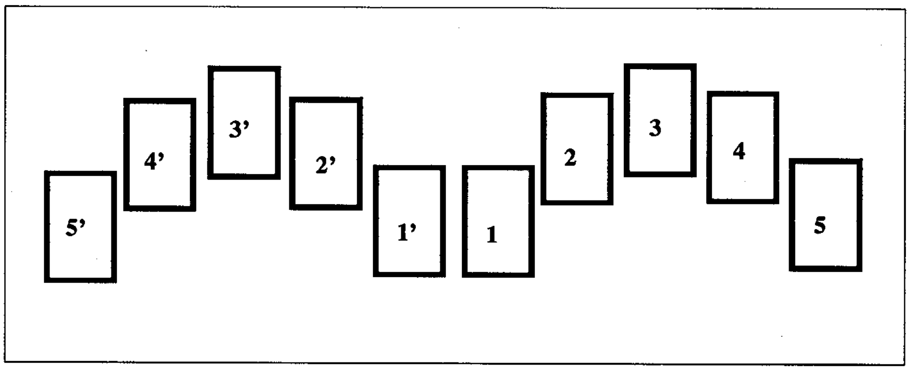

Figure 6 Gopher two-hand chord keyboard

2.3 Comparisons of QWERTY and Chord Keyboards

Figure 7 compares and contrasts keyboard operations for QWERTY and Stenograph: in general, the major steps are similar, but specifics differ. Operation of both types of input interfaces requires moving through linguistic, psycho-linguistic, pscho-motor and motor phases to get from the input to the output. However, what precisely takes place at each of these levels differs for the two types of keyboards. For example, in using the QWERTY keyboard, once a operator hears a word, the operator must retrieve from a look-up dictionary the letters for that word; in using the Stenograph, the user need only decide how to break the word into syllables, with several variants often being acceptable. The contrast in naturalness of these various activities is significant: orthographic systems are highly conventional, non-natural levels of language representation, and typing on QWERTY requires moving through this intermediary; syllable divisions, on the other hand, represent natural boundaries in the speech chain, and evidence gleaned from studies of speech errors suggests that the syllables individually represent significant linguistic entities [29]. Stenograph recording thus appears at this level to be linguistically more natural than its QWERTY counterpart. At the level of psycho-motor activity, the QWERTY operator must associate the conventional spelling, which may be from 1 to 20 letters in length, with a set of sequential finger motions; the Stenograph operator must associate a single syllable at a time, of strictly constrained overall phonetic contour, with the finger positions for a uniquely associated chord. In motor activity, the QWERTY operator depresses keys sequentially from a word's beginning until the end of the word is reached, at which point he types a space — the word delimiter — and begins the process over for the next word; in this activity, there are significant chances of transposing sequential letters inadvertently. The Stenograph operator depresses the keys of his selected chord all at once, release them all simultaneously and proceeds directly to the next syllable for processing and recording; here, assuming the correct keys have been selected, there is no possibility of transposition, since key order is rigidly fixed. At each levels of operation, then, the Stenograph keyboard appears to deal with relatively more natural linguistic units than QWERTY, with code generation proceeding in a more appropriately constrained way.

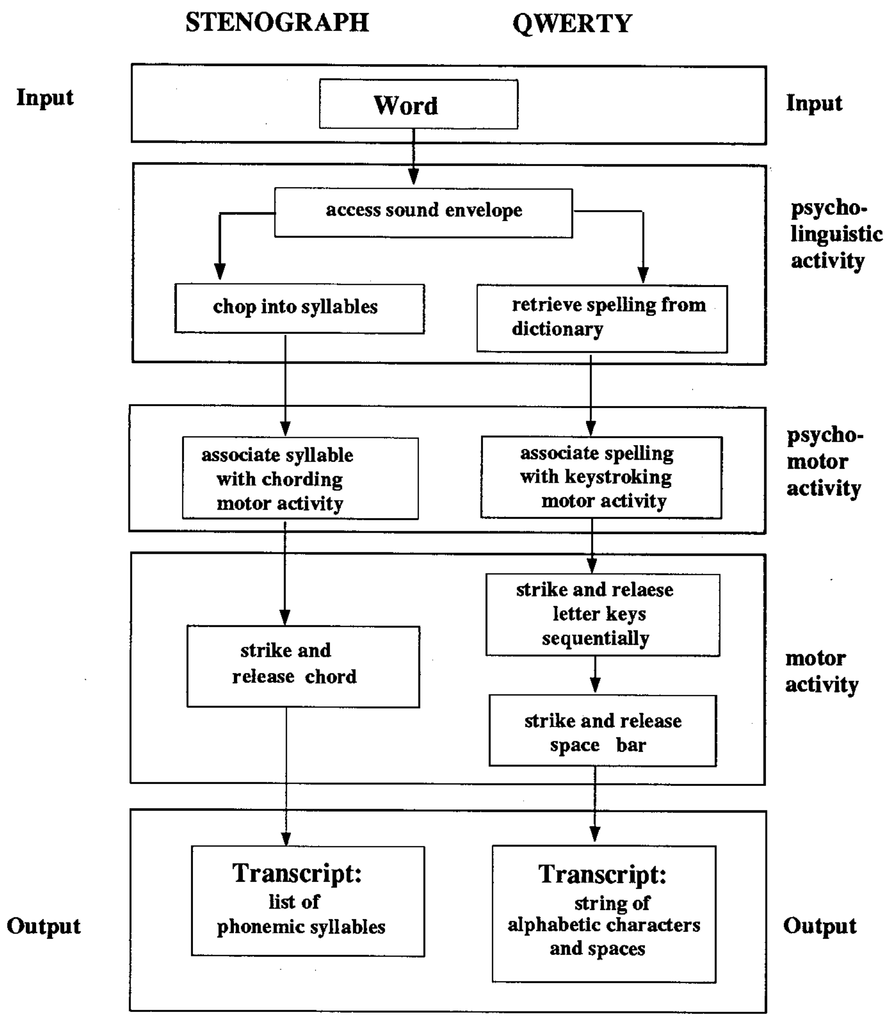

Figure 7 Encoding Sequence on Stenograph and QWERTY

Gopher and Raij (1988, [28]) contrasted the learning rates and typing performance of three groups of subjects typing free text. Six subjects were trained on the two-hand chord keyboard, five subjects were trained with the single-hand version (only the right plate of the two-hand keyboard). A third group of four subjects was trained on the regular QWERTY keyboard.

Subjects in both chord keyboard groups were able to memorize the complete set of chords in a period ranging from 30–45 min. Subjects practicing the QWERTY keyboard were able to memorize the position of the set of 22 letters in a similar period, ranging from 30–45 min. However, while typing during later sessions, they continuously used visual supervision to guide their fingers.

Figure 8 presents the learning curves of the 2 experimental groups during 35 h of training. These curves are based on average typing rates (character/min) per session. Error rate in all groups were low, ranging between 1% and 2% throughout training. Two of the subjects in the two-hand chord keyboard group continued their training up to 50 h. Their typing level at that point was 51 WPM (255 characters/minute). One of them continued up to 60 h and reached a rate of 59 WPM (295 characters/minute). For both subjects, the error rate remained constant at their low 1% level.

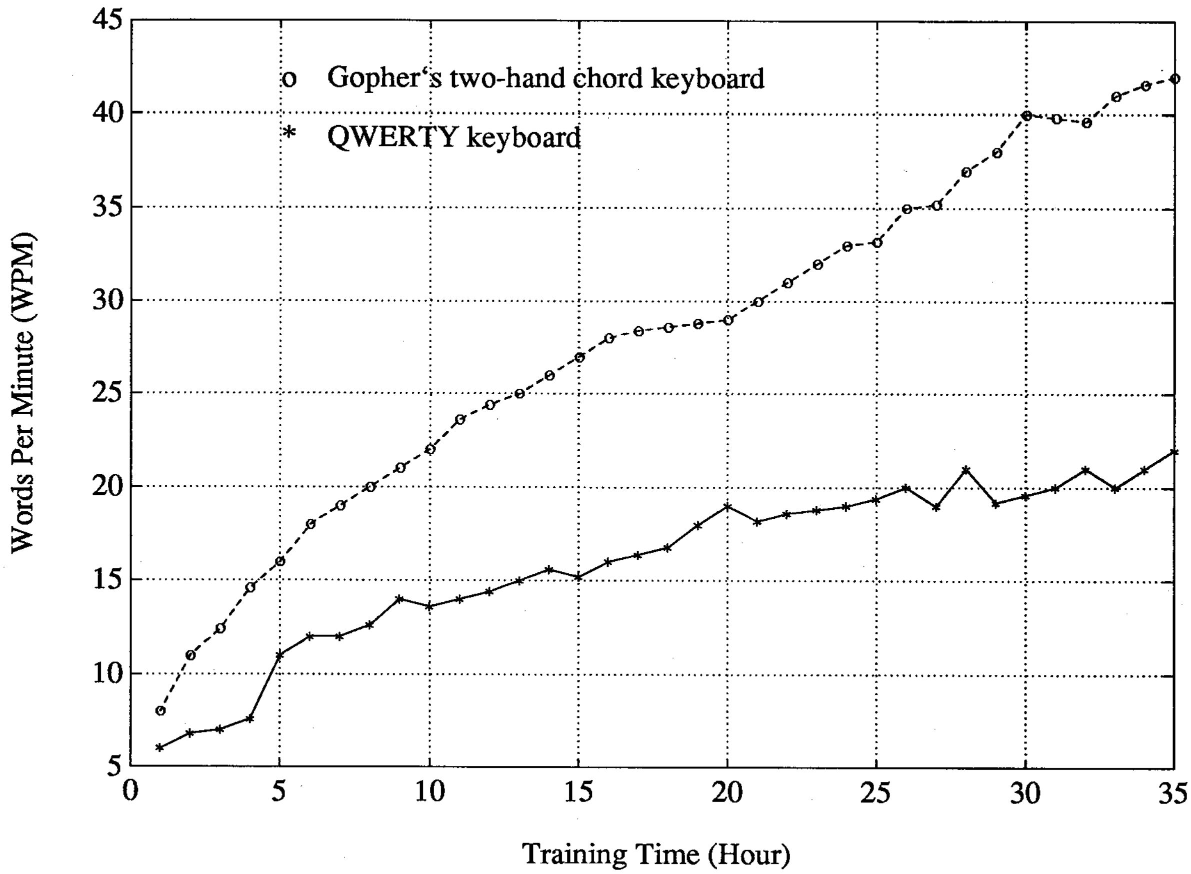

Figure 8 Learning curves of 2 groups typing free text two-hand chord keyboard and on QWERTY keyboard.

2.4 Discussion

The principal requirement for the ability to type on QWERTY keyboard is some internalization of the spatial coordinates of the keyboard and the location of all keys. The aims are to acquire the capability for blind positioning of fingers on their intended letter keys and the knowledge of the movement trajectories of hands and fingers from one key to another. These aims are hard to achieve, because the number of keys is large, there are ten simultaneous operators (fingers) and hundreds of finger trajectories that have to be mastered. But, one principal feature we should notice is that the QWERTY keyboard ensures that almost all keystrokes alternated from one hand to the other [30], whether by accident or by design. These overlapped hand or finger movements account for some very fast typing reported (but not as fast as spoken speech).

There is controversy about the worth of a stenotypist as shown by the quotation below which implies that the area is held in poor repute: "the job title stenotypist has been in sharp decline in recent years" [31]. It is generally felt that the stenograph machine is difficult to learn. Usually it takes upwards of three years for a stenotypist to acquire the necessary skills. This is probably due to the following disadvantages:

1. With unsuitable coding between phonemes and keys, some frequently used phonemes correspond to complex combinations of keys. Operators have to sustain some unnatural typing postures, which lead to the decrease of typing rate.
2. Long words must be split into a succession of syllables. Selecting the correct syllables on the fly from spoken speech is very difficult to visualize. The syllable concept imposes a large extra cognitive task on the operator.
3. Without alternate typing between two hands, the typing rate may be potentially limited.

The Gopher and Raij's experimental results indicate a clear performance advantage of Gopher's two-hand chord keyboard over the QWERTY keyboard. This keyboard is based on simpler and powerful cognitive and motor organization principles. Operators typing on the QWERTY are required to acquire many reach movements — fingers and hand trajectories, while such a requirement does not exist on the Gopher's chord keyboard. In the Gopher's keyboard, hands and fingers rest on their home keys at all times and no travel is required.

Chapter 3 Minimum Chord Stenograph Keyboard Design

Based on the discussions in the last Chapter, the new stenograph chord keyboard was designed with three aims in mind: to minimize the number and difficulty of reach movements; to maximize the alternate typing; to facilitate comfortable finger posture and to ease the memorization of coding. This Chapter will present a new stenotype keyboard, called the Minimum Chord Stenograph (MCS), with detailed description and discussions. In the next section we present the new stenograph keyboard layout; in the section 3.2, a suboptimum coding in MCS keyboard is developed to maximize the operators' information rate; in the section 3.3, the implementation of MCS is described; and finally a number of particular features embodied in the MCS keyboard are discussed.

3.1 MCS Keyboard Layout

In our work, we choose 41 phonemes, 24 consonants and 17 vowels, which can be used to produce very intelligible speech ([32, 33]). Therefore, there are 41 phonemes for speech as against 26 alphabet letters for written text in English. The input rate in phonemes/minute is likely to fall below the characters/minute achieved by Gopher and Raij. The information per phoneme is $log_2 41 = 5.36\ bits$ as against the $log_2 26 = 4.7\ bits$ for letters. The number of phonemes per word is smaller than the number of the letters per word. From another point of view, the text information is probably the same whichever way it is encoded. If we can find a minimum chord layout for phonemes like the layout for letters, the human task should be equivalent and the performance in words per minute should be similar using either approach.

A possible chord layout for phoneme input is suggested here. In this proposed layout, the fingers are generally above particular keys. Each finger thus has only to move in one direction, up or down. The basic layout will allow exact phonemic descriptions of the text to be entered. The input mode is called full phonemic (FP).

With 4 fingers and a thumb, there are 5 variables, hence $2^5 - 1 = 31$ possible codes from one hand. In English 41 phonemes must be coded. We can increase the total of possible codes to $2^6 - 1 = 63$ by allowing the thumb to move sideways. The keyboard layout, to be called the Minimum Chord Stenograph (MCS), showing principal keys, is shown in Figure 9.

The 4 fingers of the right hand rest above keys 2, 3, 4 and 5; the thumb rests above keys 0, 1 or the pair 0 and 1. The index finger can operate key 2, the middle finger will operate key 3 and so on. The thumb must be able to depress key 0, key 1 or the pair of key 0 and key 1. Thus the strong thumb is required to move in two directions; the fingers only have to move in one direction. The fingers and thumb of the left hand are similarly sited above the 2',3', 4', 5' and 0', 1' respectively. Mirror-symmetric mapping is used.

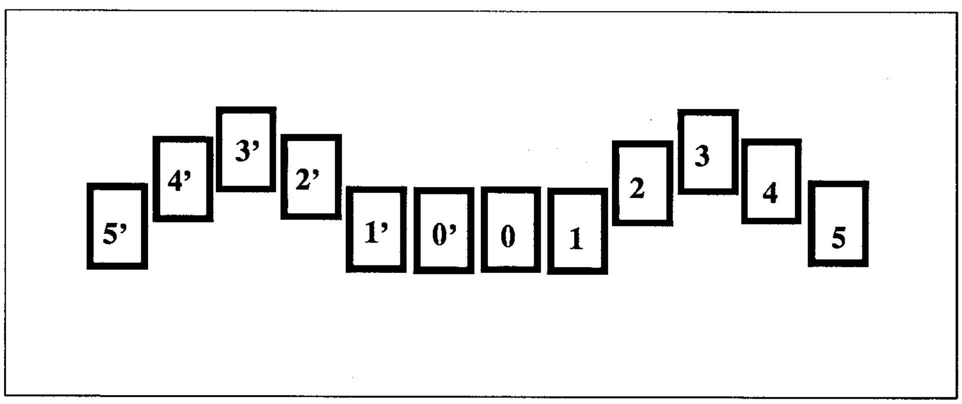

Figure 9 Keyboard Layout for MCS

3.2 MCS Coding

We use DECtalk symbols [32] to represent the 41 phonemes. The correspondence between phonemes and their pronunciations is given in Table 2 and Table 3.

Table 2 English Vowel Phonemes

DECtalk Symbol	Example
ae	b*a*t
ah	b*u*t
ao	b*o*b
aw	b*ou*t
ax	*a*bout
ay	b*i*te
eh	b*e*t
er	b*ir*d
ey	b*a*ke
ih	b*i*t (stressed)
ix	Denn*i*s (unstressed)
iy	b*ea*t
oy	b*oy*
ow	b*oa*t
uh	b*oo*k
uw	l*u*te
yu	c*u*te

Table 3 English Consonant Phonemes

DECtalk Symbol	Example
b	***b***in
ch	***ch***in
d	***d***in
dh	***th***is
f	***f***in
g	***g***ift
hx	***h***en
jh	***j***am
k	***k***in
l	***l***et
m	***m***et
n	***n***et
nx	si***ng***
p	***p***in
r	***r***un
s	***s***in
sh	***sh***in
t	***t***in
th	***th***in
v	***v***an
w	***w***in
yx	***y***es
z	***z***en
zh	azure

Each of the 41 phonemes, x $(x = 1, 2, ..., 41)$, has a probability $p(x)$. The information contained in receiving the (isolated) phoneme is

$$I(x) = -log_2 p(x) \ bits. \tag{3.1}$$

The information relative to the other phonemes in the phoneme alphabet is the entropy $p(x)I(x)$. If the time allowed a phoneme is $t(x)$ then,

$$C(x) = p(x)I(x)/t(x) \ bits/second \tag{3.2}$$

is the channel capacity, the average information rate in bits/second, needed to transmit the phoneme without distortion. Thus the flow of information along the channel will be

$$\sum_{x=1}^{41} -p(x)log_2 p(x)/t(x) = \sum_{x=1}^{41} C(x), \tag{3.3}$$

and the $t(x)$ are to be chosen to maximize the quantity without exceeding the channel capacity C, i.e.

$$C(x) \leq C. \tag{3.4}$$

For a single phoneme, x, we note that its information contribution is $C(x)$. Ideally, $C(x)$ should not exceed C: neither should it be much less than C. Thus optimum coding is obtained with equality in equation 3.4. With this in mind, we could say information flow is constant with time irrespective of the phoneme being transmitted. Unfortunately this optimum is unlikely.

However, we can obtain a suboptimum solution by ordering the $t(x)$ and the $p(x)$ according to equations 3.5 and 3.6 below.

$$p(1) > p(2) > ... > p(x) > ... > p(N). \tag{3.5}$$

$$t(1) < t(2) < ... < t(x) < ... < t(N). \tag{3.6}$$

Thus we can set the coding for any phoneme from measurements of the response time for hand movements and on this basis we can assign a phoneme x a specific hand movement.

The relative frequency of appearance of vowels and consonants in the English language [34, 35] is given by Table 4 and Table 5 respectively.

Table 4 The Relative Frequency of English Vowels

Vowel	Relative Frequency (%)
ax	4.63
ix	4.42
ao	4.16
ih	4.11
ae	3.50
eh	3.44
iy	2.12
ey	1.84
ah	1.70
uw	1.60
ay	1.59
ow	1.30
uh	0.69
er	0.63
aw	0.59
yu	0.05
oy	0.03

Table 5 The Relative Frequency of English Consonants

Consonant	Relative Frequency (%)
n	7.24
t	7.13
r	6.88
s	4.55
d	4.31
l	3.74
dh	3.43
z	2.97
m	2.78
k	2.71
v	2.28
w	2.08
p	2.04
f	1.84
b	1.81
h	1.81
nx	0.96
sh	0.82
g	0.74
yx	0.60
ch	0.52
jh	0.44
th	0.37
zh	0.05

Similarly, a table of response times, under ideal laboratory conditions, for single-hand chords is provided by Seibel [36]. Single key responses are the fastest, but for chords involving two or more keys it is necessary to consider the specific patterns of keys in order to assess the difficulty of the chord. Table 6 presents the response times of the chords and error percentages for the highly practiced subjects in the Seibel's study.

Since the mirror-symmetric mapping is used between the two hands, here we just investigate the coding for the right hand. To make the coding easy to memorize, we differentiate between consonants and vowels. The 24 consonants can be coded just using the chord combinations from key 1 to key 5; and for vowels, the thumb will always stroke key 0 while fingers depressing the chords from key 2 to key 5. Therefore, between vowels and consonants, the thumbs have to relocate so that the consonants and vowels can not be mixed up.

Table 6 The Average Reaction and Percentage Error for 31 Chord Patterns

Pattern					Response time	Error
1	2	3	4	5	(msec)	(%)
			4		281	5.9
		3			285	2.4
1					289	1.8
	2				292	5.0
				5	296	5.6
1			4		306	3.8
	2	3			306	8.8
		3	4		306	10.3
1	2				310	6.2
	2	3	4		311	9.1
1		3			312	5.0
1	2	3	4		314	4.1
1	2	3			315	5.3
1				5	315	5.6
			4	5	316	11.5
	2		4		316	12.1
	2	3	4	5	317	4.4
1		3	4		320	10.6
		3	4	5	321	7.6
1	2	3	4	5	325	7.4
	2			5	326	12.4
1			4	5	328	8.2
1	2		4		328	13.2
1		3	4	5	330	12.4
1	2			5	335	11.8
		3		5	343	13.2
1	2	3		5	345	18.8
1		3		5	349	15.0
	2		4	5	349	20.9
1	2		4	5	351	25.9
	2	3		5	352	22.1

It is difficult for an operator to manipulate his fingers to strike some of the 31 chords. The order of relative difficulties of 24 easier chords out of 31 possible chords from key 1 to key 5 according to response time is given by Table 6 as follows

$$\{4\},\{3\},\{1\},\{2\},\{5\},\{1,4\},\{2,3\},\{3,4\},$$
$$\{1,2\},\{2,3,4\},\{1,3\},\{1,2,3,4\},\{1,2,3\},$$
$$\{1,5\},\{4,5\},\{2,4\},\{2,3,4,5\},\{1,3,4\},$$
$$\{3,4,5\},\{1,2,3,4,5\},\{2,5\},\{1,4,5\},$$
$$\{1,2,4\},\{1,3,4,5\}.$$

Now we can link the consonants to the best in a suboptimum sense single-hand chords. The coding between keys and consonants for the right hand is shown in Table 7.

In the same way we can discuss the coding between keys and vowels. In this case the chords coded to consonants can not used here. The relative difficulties of the chords, which are formed by key 0,1,2,3,4, and key 5, can be ordered by response time as follows:

$$\{0\},\{0,4\},\{0,2\},\{0,1\},\{0,3\},\{0,2,3,4\},$$
$$\{0,2,3\},\{0,5\},\{0,3,4\},\{0,2,3,4,5\},\{0,4,5\},$$
$$\{0,2,4\},\{0,3,4,5\},\{0,2,5\},\{0,2,3,5\},\{0,3,5\},$$
$$\{0,2,4,5\}.$$

Therefore the coding between keys and vowels for the right hand is given in Table 8.

Table 7 Coding Between Keys and Consonants

Consonant	Chord	Example
n	{4)	net
t	{3}	tin
r	{1}	run
s	{2}	sin
d	{5}	din
l	{1,4}	let
dh	{2,3}	this
z	{3,4}	zen
m	{1,2}	met
k	{2,3,4}	kin
v	{1,3}	van
w	{1,2,3,4}	win
p	{1,2,3}	pin
f	{1,5}	fin
b	{4,5}	bin
hx	{2,4}	hen
nx	{2,3,4,5}	sing
sh	{1,3,4}	shin
g	{3,4,5}	gift
yx	{1,2,3,4,5}	yes
ch	{2,5}	chin
jh	{1,4,5}	jam
th	{1,2,4}	thin
zh	{1,3,4,5}	azure

Table 8 Coding Between Keys and Vowels

Vowel	Chord	Example
ax	{0}	about
ix	{0,4}	Dennis(unstressed)
ao	{0,2}	bob
ih	{0,1}	bit(stressed)
ae	{0,3}	bat
eh	{0,2,3,4}	bet
iy	{0,2,3}	beat
ey	{0,5}	bake
ah	{0,3,4}	but
uw	{0,2,3,4,5}	lute
ay	{0,4,5}	bite
ow	{0,2,4}	boat
uh	{0,3,4,5}	book
er	{0,2,5}	bird
aw	{0,2,35}	bout
yu	{0,3,5}	cute
oy	{0,2,4,5}	boy

3.3 MCS Implementation

3.3.1 Boswell Keyboard System

The Boswell keyboard system is a fully portable device which can be connected to and communicate with a microcomputer using a standard serial interface.

The system consists of an electronic circuitry mounted on a printed circuit board. The printed circuit board is in the form of a chassis. Included on the printed circuit board chassis and forming an integral part of the system is a unique arrangement of depressible key switches arranged in a manner conducive to ease of use by operators. Also included on the printed circuit board chassis is a set of communication receptacles for audio output, video output, serial computer connecting and parallel computer communications. Furthermore, a screen is mounted on the printed circuit board chassis and indicates the current data string in phonetic alphabet and current word processing command.

The electronic circuitry of the Boswell System mainly consists of the following:

1. Central Processing Unit (CPU, Z80180–PS chip): The CPU manages all operations of the whole system according to the instructions stored in a EPROM chip.

2. Memory (one EPROM 27256 chip and six RAM 62256 chips):
    a. EPROM stores all instructions to be executed by the CPU and the coding between keys and phonemes used to convert various keystrokes to sounds and displayed data.
    b. RAM stores information as decided by each keyboard user. The CPU can read and write to this memory.
3. Speech Synthesizer (Artic 263A chip):

    The Artic is capable, under CPU control, of generating a reasonable approximation of any sound, which can be fed to a headphone.
4. Keyboard Control System (one integrated circuit TMPZ84C20P):

    This device is under synchronous CPU control and it scans the pressed key patterns. The pressed key pattern is read by CPU.
5. Liquid Crystal Display (LCD, Sharp LM16155):

    This display presents to the viewer, as a single line of 20 characters, any data that is written to it by CPU.
6. Host Communications (Part of Z80180–PS and one integrated circuit MAX232C):

    Under CPU and program control, information can be written to and read from the communications port through this circuitry.

3.3.2 MCS Implementation

MCS system was implemented by replacing the EPROM chip in the above Boswell system with another EPROM chip, which stores the necessary instructions and the MCS coding instead of the Boswell coding.

A set of software was written in C to generate target code containing the MCS coding and to load the target code from a 386 computer to the EPROM chip on MCS system through the communications port.

3.4 Discussions of MCS Keyboard Layout

There are a number of particular features embodied in the minimum chord stenograph (MCS) keyboard:

1. The efficacy of eliminating movements of the fingers away from their resting position seems self-evident. Anything that reduces the amount of movement in principle leads to faster performance and low error. This is supported by workers on chord keyboards such as Rochester, Bequaert and Sharp ([37], 1978), Gopher and Raij ([28], 1988), and many others.
2. MCS layout shows symmetry for right- and left-hands. Symmetry coding should make learning easier and faster. This feature is supported by the 1941 Palantype layout ([25], 1987), Salthouse ([38], 1986), and by Gopher, Karis and Koening ([39], 1985).

3. The efficacy of allowing hands to act in alternation arises from the ability of the currently unused hand to prepare its next strike earlier by making an anticipatory movement. The ability of overlap movements found advantageous ([40, 38], 1984 and 1986).
4. The basic input unit is the phoneme. The operator should find the phoneme easier to visualize and operate. In addition, the greater number of phonemes helps in the sense that there are about 5 letters/word as against 3.1 phonemes/word; roughly 38% data compression. This compression translates into less finger movement, which is another contribution to faster typing.
5. The association between relatively frequent phonemes and relatively easy chords optimizes the effect and leads to speedy learning. Stated in another way, there is a positive relationship between motoric ease, ease of recall and frequency of phoneme occurrence.

Chapter 4 Experiment and Results

In order to evaluate the proposed stenograph (MCS) keyboard, it is necessary to determine the answers to the following two questions:

1. Is it easier to learn with MCS keyboard than with standard stenograph keyboards like Boswell and with QWERTY keyboard?
2. Is the input rate for MCS keyboard better than the input rates with standard stenograph keyboards like Boswell and QWERTY keyboard?

Experiments with both MCS and Boswell systems were performed to answer these two questions. A program was written for the 386 computer in C which linked the 386 to the Boswell or MCS. This program is able to measure the interkey interval in striking the stenograph keys and thus able to record which finger movements are fast movements and which are slow ones in the context of Boswell or MCS input. Measurements were made while the stenograph typist was inputting material in the normal fashion. Another program was written in MATLAB to analyze and compile the experimental data. In the following two sections, the experiment procedures and the testing results are presented and discussed.

4.1 Experiment

4.1.1 Subjects

13 right handed native English speakers participated in the experiment. Subjects were paid $7.00 per hour for their participation and received an extra bonus for outstanding performance. The characteristics of the subjects are shown in Table 9. None of the subjects had previous experience of stenotyping except for subjects ME, BC, BD, and BE. Subjects were assigned to two experimental groups: MCS group and Boswell group. In MCS group, eight subjects, MA to MH, were trained and tested on MCS keyboards but three of them dropped out in the course of training because of time conflict with their courses. The top two subjects MA and MB in the table were "control" subjects. In the Boswell group, the five subjects, BA to BE at the bottom of the table, were trained and tested with standard stenograph Boswell keyboards.

Table 9 The Characteristics of the Subjects

Subject	Sighted	Sex	Age	Working Machine	Typing on QWERTY (WPM)
MA	good	F	29	MCS	40
MB	good	F	19	MCS	25
MC	poor	M	19	MCS	35
MD	no	F	29	MCS	25
ME	good	F	45	MCS	85
MF*	good	F	22	MCS	25
MG*	good	F	20	MCS	45
MH*	no	F	20	MCS	35
BA	poor	M	45	Boswell	40
BB	good	F	25	Boswell	40
BC	no	M	22	Boswell	40
BD	no	F	40	Boswell	43
BE	no	F	40	Boswell	65

The subjects marked * dropped out of the experiment after 25h training.

4.1.2 Apparatus

The subjects worked at a Boswell keyboard system or a MCS keyboard system (Figure 10). The input syllables or phonemes and the corresponding interkey intervals, with an accuracy at 5 msec, were recorded by a 386 computer through the communications port. As speech or text were typed, they were spoken out through a headphone and displayed on a screen in the both systems. The input text in phonemic form and the corresponding interkey intervals were also displayed on the computer's screen.

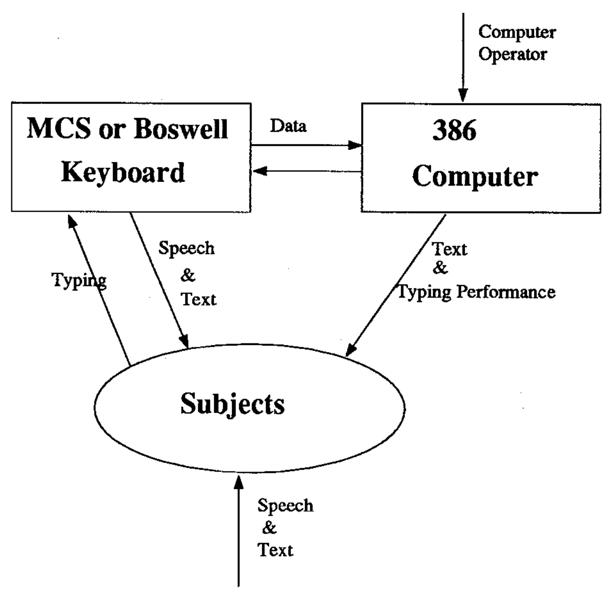

Figure 10 Block Diagram of Apparatus Setup

4.1.3 Procedure

In both the MCS and the Boswell experimental groups the charts or recorded tapes describing the keyboards were presented to sighted or blind and visually impaired subjects respectively. Subjects were asked to commit all coding to memory. They were free to try chord combinations on the keyboards and listen to the speech and/or view the typed symbols on the keyboard screen or computer screen. They were not allowed to begin actual typing before they could type, upon request, all coding on the keyboards, in random order, without error.

In the MCS group, two control subjects MA and MB participated in 20 two-hour training sessions (two other sighted subjects dropped out after about 12 sessions). There were three to four sessions a week. During each session they were tested once; three subjects MC, MD and MH (MH dropped out after 29 hours of learning) and one professional stenotypist ME were given the keyboards at home and tested once a week. In each meeting all subjects typed from a text or speech of 300 most frequently used words, and grade 5 and 10 history books; were instructed to try and alternate hands continually, typing successive phonemes by right-left alternations, and were given the same instructions as Gopher and Raij [28] done in their experiment: "You should type as fast as you can. However, accuracy is important. Do not try to trade speed for accuracy." At the ending of each meeting subjects were presented their learning curves for speed and error measures up to that meeting.

In the Boswell group, two novice subjects BA and BB participated in 50 hours of training. They were asked to practice for three to four sessions each week, each session lasting two to three hours. The visually impaired subject BA was given the Boswell keyboard at home and used the recorded tape tutorial. The sighted subject BB used a computer tutorial developed by Boswell Company. Three experienced blind subjects BC, BD and BE participated in 20 two-hour testing sessions (BE withdrew after 12 sessions). There were one to two sessions a week. During each week, all subjects were tested once.

The test material is composed of simple sentences and was designed by Boswell Company. Both keyboard groups were tested on the same material.

4.2 Results

4.2.1 Results with MCS

Initial Acquisition

Although no specific methods of learning or memorization were used in the experiment, the general finding was that subjects were able to commit to memory the codes for all phonemes within 2.5 to 11 hours (Table 10). Not much difference between sighted subjects and blind or visually impaired subjects was observed. The mean times of learning code are 6.8 h, 6.7 h and 7 h for all subjects, the sighted, and for blind and visually impaired subjects, respectively.

Table 10 Initial Acquisition on MCS

Subject	Initial Acquisition Time (h)	Sighted
MA	11	good
MB	5	good
MC	9	poor
MD	4	no
ME	2.5	good
MF	9	good
MG	6	good
MH	8	no

Typing Free Text

Figure 11 presents the learning curves of the five subjects during 40–50 h of training. These curves are based upon average typing rates per session. With 40 h of training, the two control subjects MA and MB could reach entry rates about 52 WPM and 41 WPM respectively; with 42 h of training, the visually impaired subject MC could type at 39 WPM; and with 50 h of training, the blind subject MD could reach about 47 WPM; with 45 h of training, the professional stenotypist ME could type at about 52 WPM. Error percentages were low, ranging between 1 and 7 percent throughout training. Our analysis of performance was, therefore, based primarily upon typing rates.

Differences in the rate of progress were obtained by computing the slopes of the learning curves in the last five tests for every subjects. The average slope values for subjects MA, MB, MC, MD and ME were 1.41, 1.48, 0.83, 0.73 and 0.82 WPM per hour respectively.

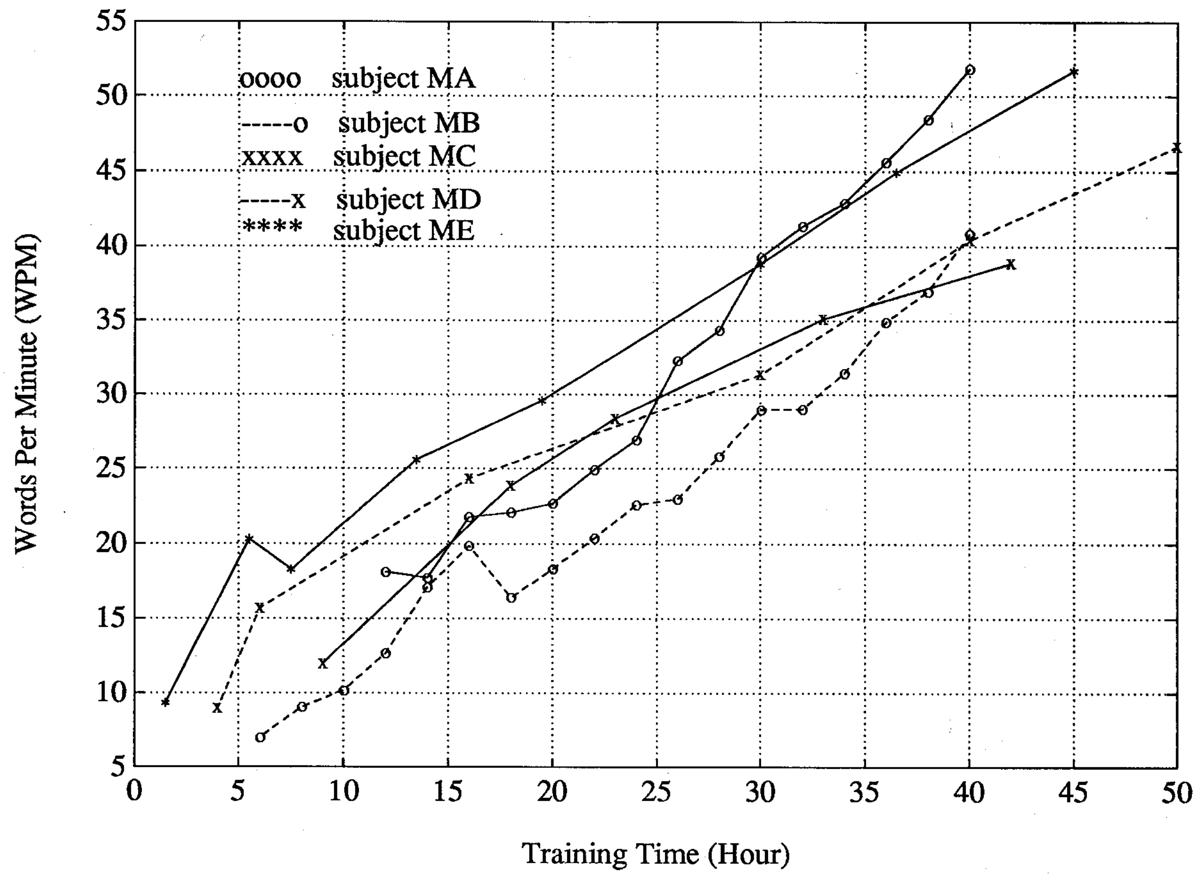

Figure 11 Learning Curves for Subjects with MCS keyboard

Changes in Speed

The most prominent learning change is well known: typists get faster with practice. Figure 12 illustrates this progression by showing the interstroke interval distribution for the 5 subjects in their first and last tests. For example, the distribution for subject MD reflects an order of magnitude differences in performance from 8 WPM at 6 hours to 47 WPM at 50 hours. There are corresponding decreases in both the mean interstroke interval (***m***) from 1743 to 355 msec and the standard deviation (***s***) from 738 to 130 msec.

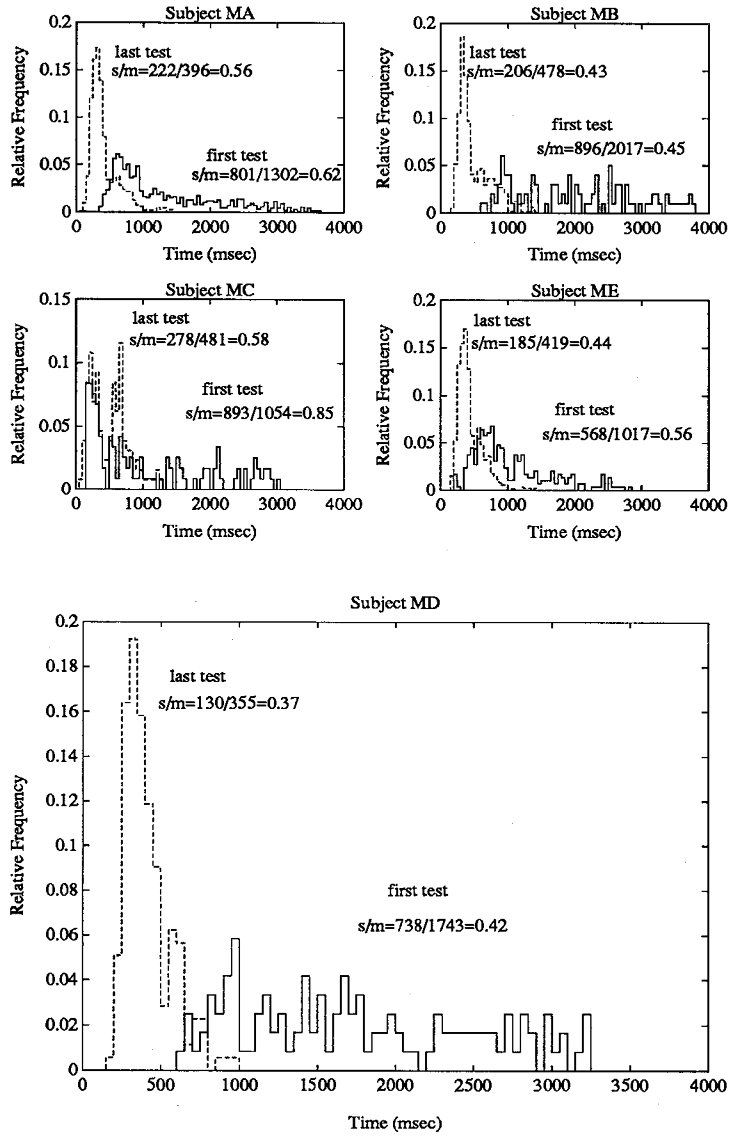

Figure 12 The distribution of interstroke intervals for subjects with MCS in the first and last tests

Response Time to Phonemes

Chord combinations for the 41 phonemes differ from each other in the position and number of fingers, and the combination of pressed and unpressed keys. As a result they create a gradient of difficulty. Since the easier chords were assigned to the more frequent phonemes in English, it is, therefore, not surprising that a range of differences between response times to phonemes is observed.

With training, the mean, ***m***, of response time to phonemes falls considerably. Plots of means of response time to consonants and vowels with the two sighted subjects in the last two tests and in the first tests are given in Figure 13 and Figure 14 respectively. The phonemes are listed in order of probability from left to right. Tables 11 and 12 present the values of the response time to consonants and vowels by averaging the results in the last two tests with two control subjects MA and MB.

Because of the relatively small sample of testing material, the response time to consonant "zh" was not observed. The response times to some consonants such as, "sh", "yx", "jh", and "th" shown in Figure 13 were very inconsistent. This was probably due to the fact that the frequency of occurrences of these consonants was very small and the subjects did not get enough training with them.

The response times in this experiment shown in Tables 11 and 12 are longer than the values reported by Seibel [14] shown in Table 6, but the ordering of the chords according to response time is similar in this experiment to Seibel's. Their rank-order correlations are 0.7568 for consonants and 0.8707 for vowels. The F ratio can be used to test the significance of the correlations. Both correlations were highly significant, $F_{Consonant}(1/44) = 27.52,\ \alpha < 0.01$ and $F_{Vowel}(1/32) = 26.37,\ \alpha < 0.01$.

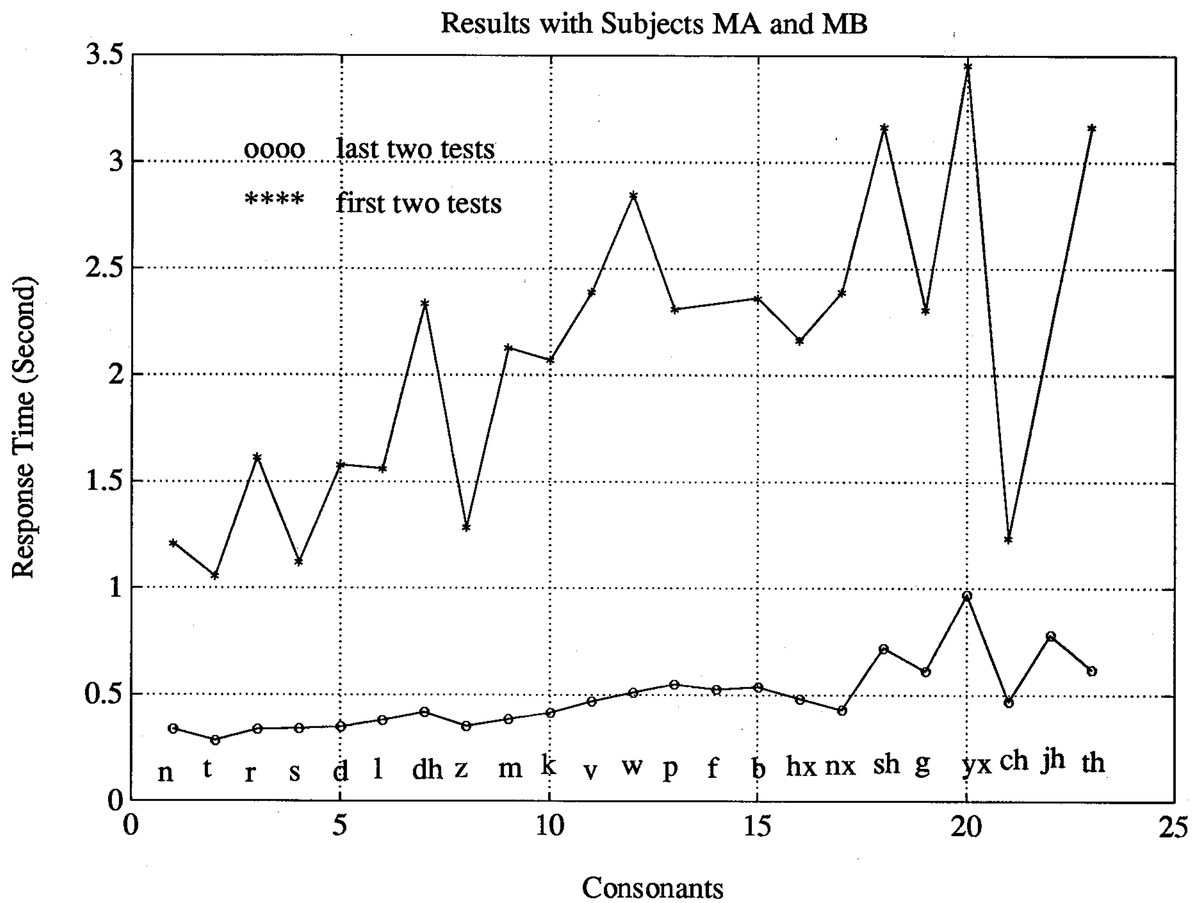

Figure 13 Response Time to Consonants

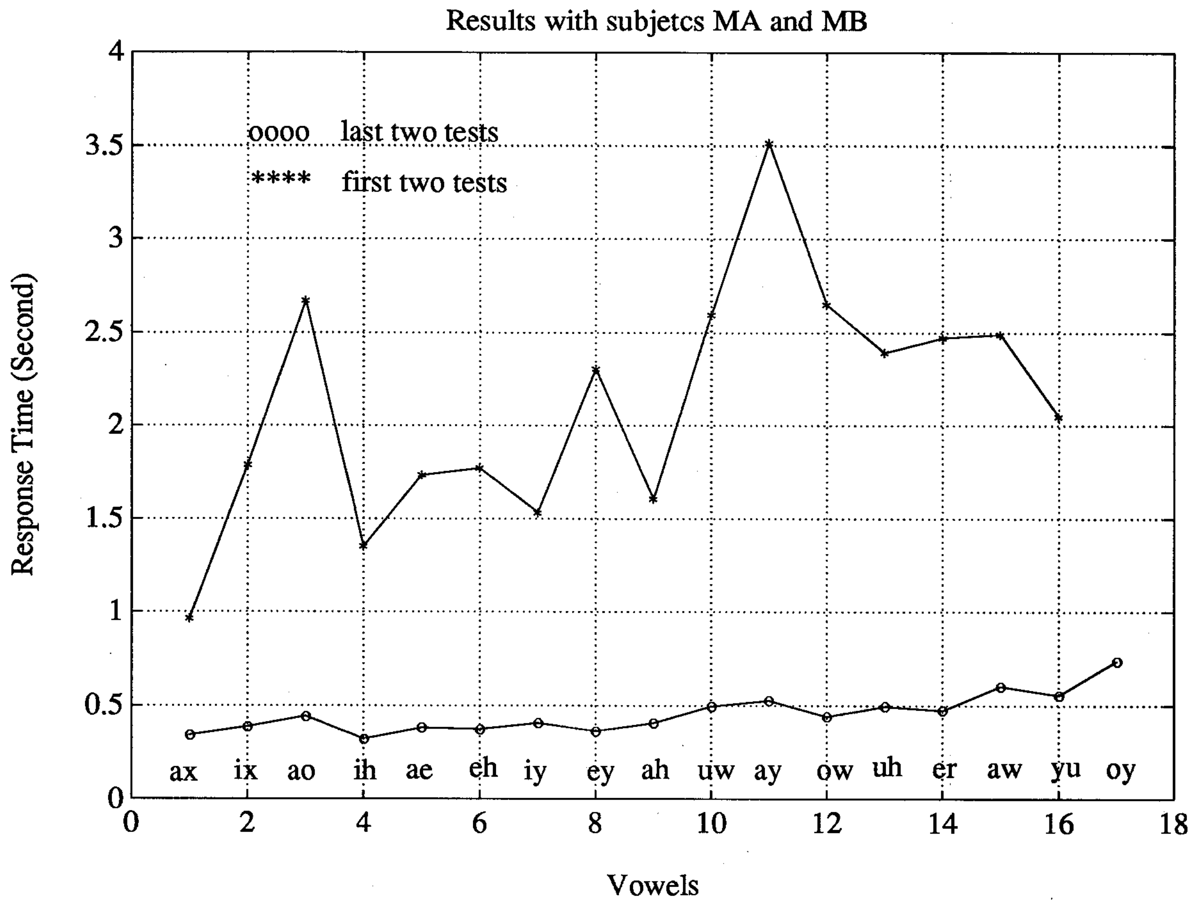

Figure 14 Response Time to Vowels

Table 11 Average Response Times to Consonants for Two Control Subjects

Consonant	Chord	Response Time (ms)
n	{4)	339
t	{3}	286
r	{1}	337
s	{2}	341
d	{5}	349
l	{1,4}	381
dh	{2,3}	418
z	{3,4}	401
m	{1,2}	385
k	{2,3,4}	416
v	{1,3}	469
w	{1,2,3,4}	511
p	{1,2,3}	550
f	{1,5}	527
b	{4,5}	538
hx	{2,4}	482
nx	{2,3,4,5}	430
sh	{1,3,4}	722
g	{3,4,5}	612
yx	{1,2,3,4,5}	970
ch	{2,5}	469
jh	{1,4,5}	782
th	{1,2,4}	620
zh	{1,3,4,5}	N/A

Table 12 Average Response Times to Vowels for Two control Subjects

Vowel	Chord	Response Time (ms)
ax	{0}	343
ix	{0,4}	387
ao	{0,2}	443
ih	{0,1}	323
ae	{0,3}	382
eh	{0,2,3,4}	374
iy	{0,2,3}	406
ey	{0,5}	364
ah	{0,3,4}	407
uw	{0,2,3,4,5}	496
ay	{0,4,5}	526
ow	{0,2,4}	440
uh	{0,3,4,5}	496
er	{0,2,5}	474
aw	{0,2,35}	602
yu	{0,3,5}	554
oy	{0,2,4,5}	738

It is also found that the standard deviation, ***s***, and the ratio (***s/m***) of the mean to the standard deviation fall too. Figures 15 and 16 gives the examples of the distribution of response time to consonants and vowels respectively for the best subject MA in the first and last tests. In the first tests, the standard deviation normalized to the mean, ***s/m***, is large being greater than 50%, but at the last tests the ***s/m*** falls considerably indicating more consistent operation with practice.

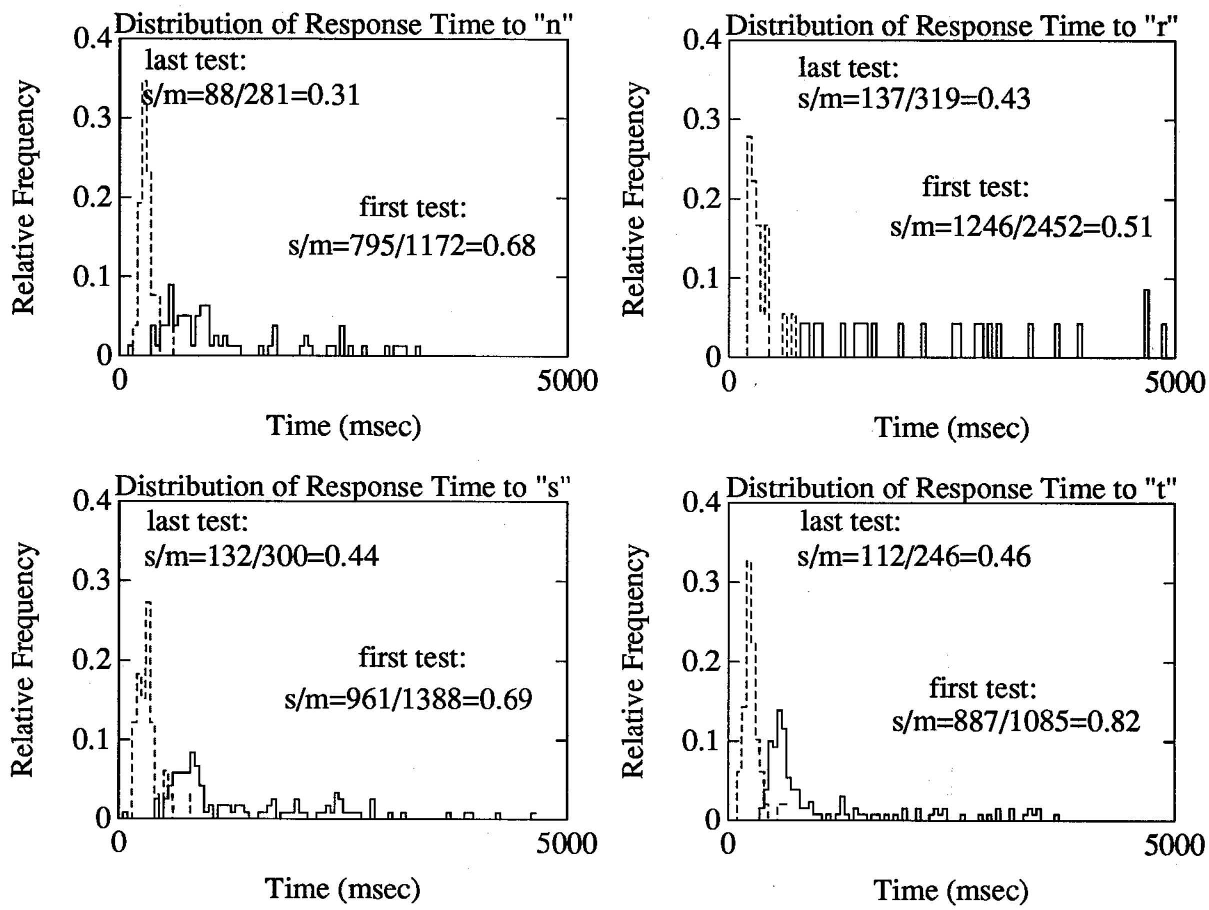

Figure 15 Examples of Distribution of Response Time to Consonants for Subject MA

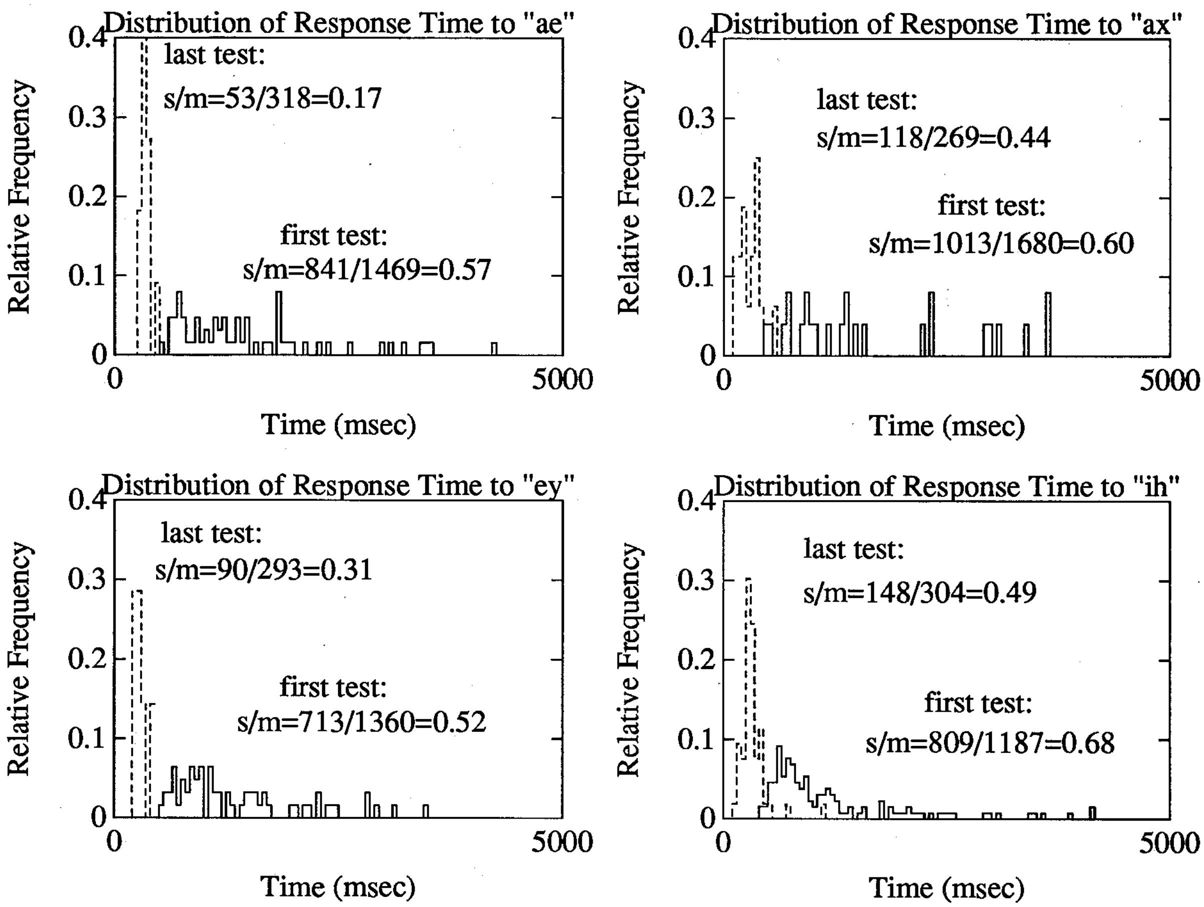

Figure 16 Examples of Distribution of Response Time to Vowels for Subject MA

Analysis of Errors

The overall number of errors in this experiment was small, because experimental instructions were designed to emphasize accuracy as much as speed. The Figure 17 presents the error rates: average figures for the two control subjects MA and MB, the visually impaired subject MC, the blind subject MD and the stenotypist ME. It can be observed that the error rates become lower with practice, from about 7% in the first test to 2% in the last test.

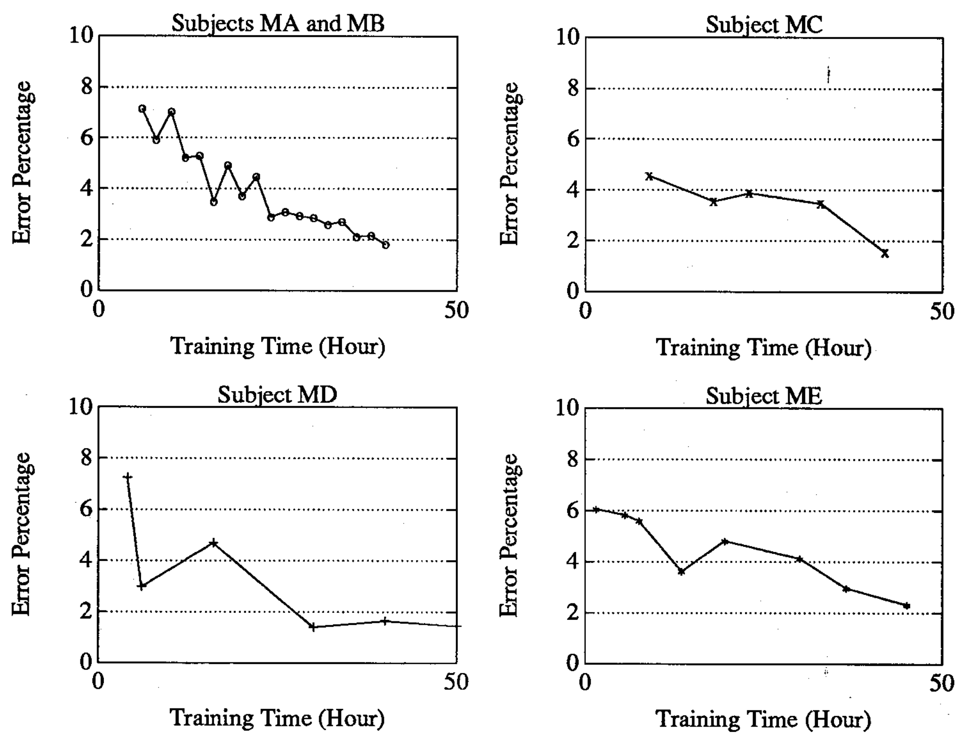

Figure 17 The Entry Error Rates for MCS Subjects

The closer examination of the entry errors revealed that errors could be generally classified into two types: *Motor* errors and *Representation* errors. Motor errors (Figure 18) were those that resulted from faulty activation or lack of activation of fingers that could be attributed to biomedical properties and constraints of the hands. In motor errors the actual typed chord and the desired chord usually comprised different numbers of fingers.

Representation errors (Figure 19) were typically these that manifested confusion between the patterns created by the replaced phonemes. Most common were left or right shifts on the panel of chords, composed of a coherent group of several successive fingers. Figures 18 and Figure 19 depict 8 examples of the more frequent motor and representation errors. The upper row in each example depicts the chord of the required phoneme, the lower row is the actual chord that was typed by mistake. The relative percentages of motor, representation and other errors from the total number were 54.89, 33.70, and 11.41 respectively.

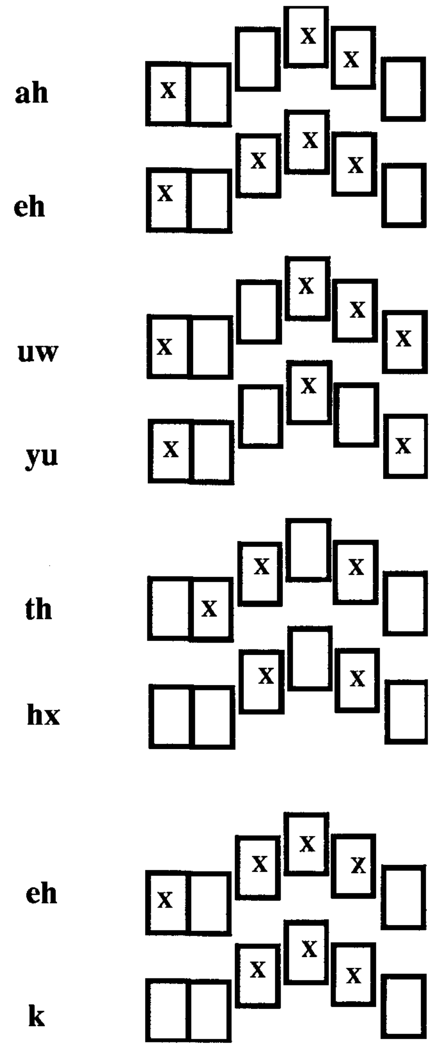

Figure 18 Examples of Motor Errors

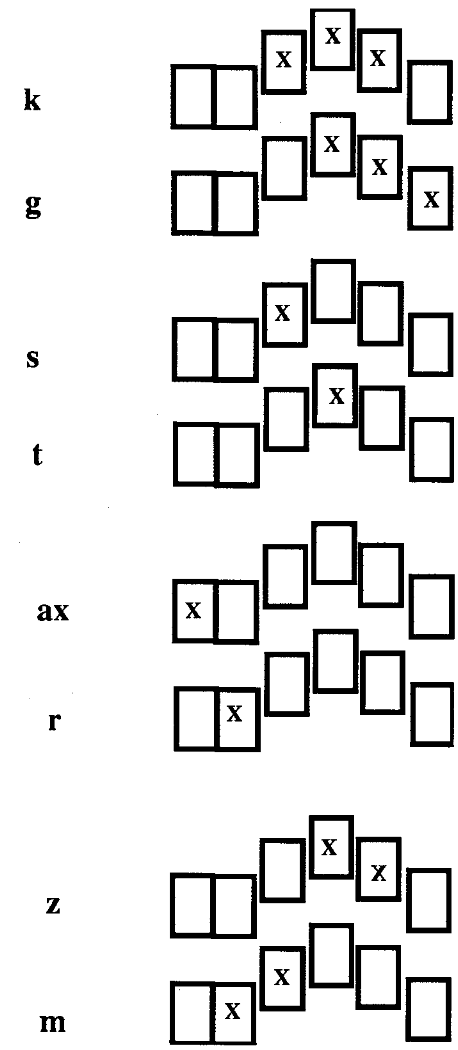

Figure 19 Examples of Representation Errors

4.2.2 Results with Boswell

Initial Acquisition

The novice subject BA (visually impaired) could operate the Boswell keyboard after 34 h learning even though he still could not commit all the Boswell coding to memory. The other novice subject BB (sighted) still could not memorize all the Boswell coding and could not operate it after 50 hour training. Both of them reported that during this training there was much to memorize. Many of the chords were found to be very difficult to operate.

Typing Free Text

Figure 20 presents the learning curve of the novice subject BA during 50 hour of training. This curve is based upon average typing rates per session. With 50 h of training, he could reach close to 25 WPM. The average learning slope is 0.64 WPM per hour.

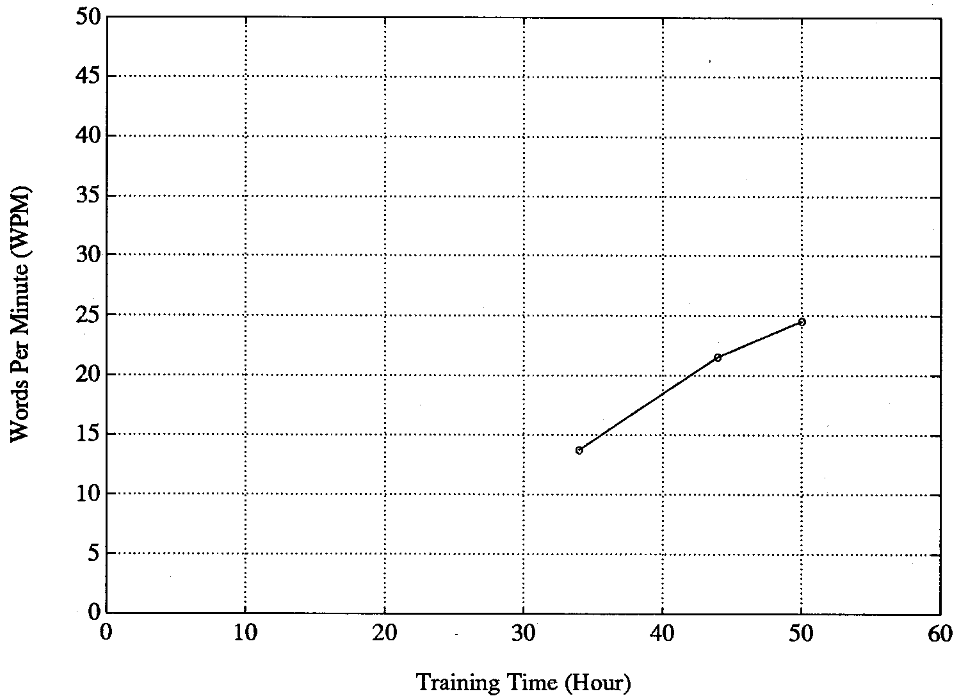

Figure 20 Learning Curve for Novice Subject BA with Boswell Keyboard

Figures 21 presents the learning curves of the experienced subjects BC, BD and BE respectively. With 85, 281 and 297 h of training, the three subjects could type about 25, 35 and 38 WPM respectively. Differences in progress rate were obtained by calculating the slopes of the learning curves in the last five tests for the three experienced subjects. The average slope values for subjects BC, BD, and BD were 0.379, 0.005, and 0.089 WPM per hour respectively.

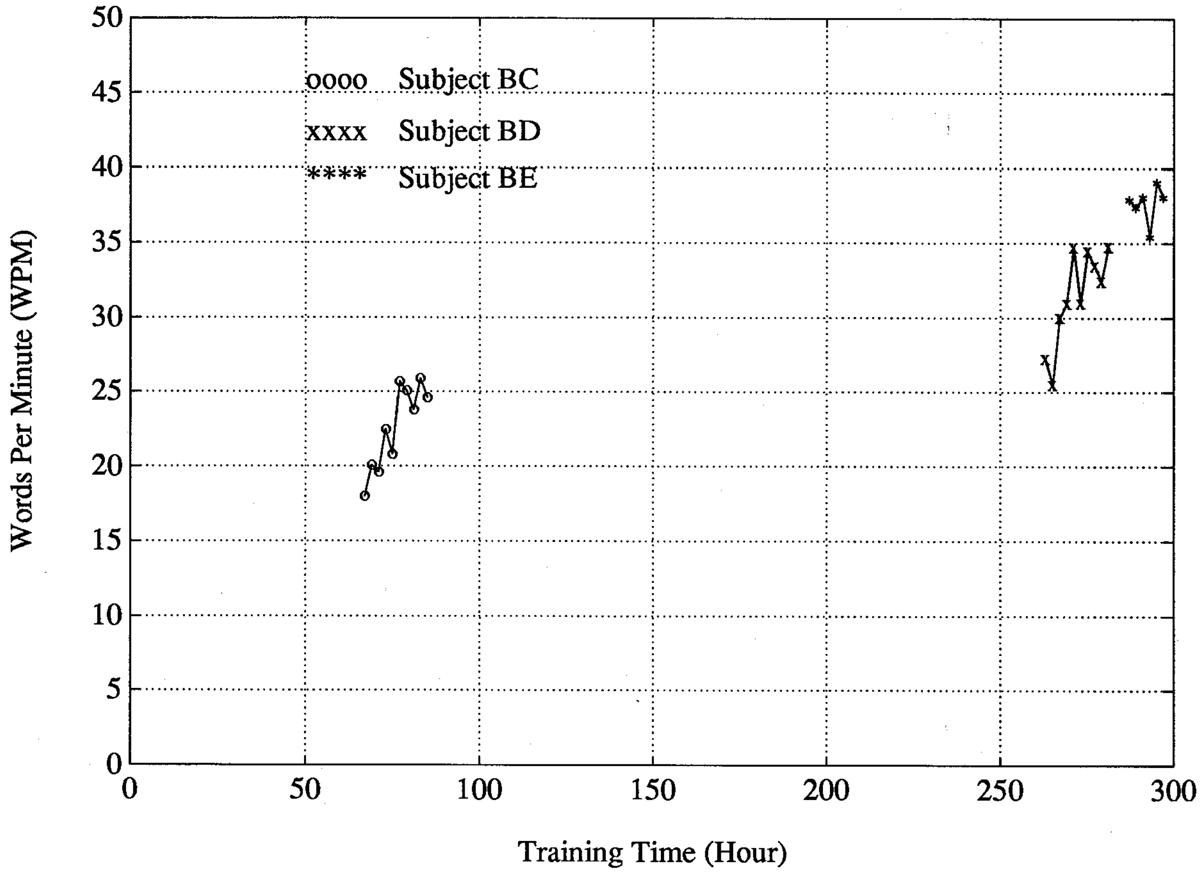

Figure 21 Learning Curve for Experienced Subjects with Boswell Keyboard

4.3 Discussions

4.3.1 Discussion on MCS Coding

For the coding to be successful in some sense, it is postulated that the typing rate of subjects should rise with training. This was verified by the experimental results (Figure 11). It is also postulated that the coding should result in a uniform information flow. A measure of success in the coding will be the uniformity of information rate which can be expressed as a normalized variance by

$$V = \frac{E\left[(C(x) - E(C(x)))^2\right]}{E\left[C(x)^2\right]}. \tag{4.1}$$

As mentioned in Chapter 2, $C(x)$ is the measure of phoneme channel information, the average information rate in bits/second, when inputting the phoneme x.

Figure 22 depicts the normalized variance vs. the average information rate. Each point in this plot was obtained from every three tests for the two control subjects MA and MB. The training hours for each point were also shown on this figure. From this figure, we can conclude that subjects get more consistent with training, in spite of increased information rate. Starting with a high variance of 9.8% when the information rate is 3.5 bits/second in the first three tests, it falls uniformly with training to 4% when the information rate is about 11 bits/second in the last three tests. The principal comfort is that the curve is monotonic and decreasing with training time. Thus training reduces the information fluctuations.

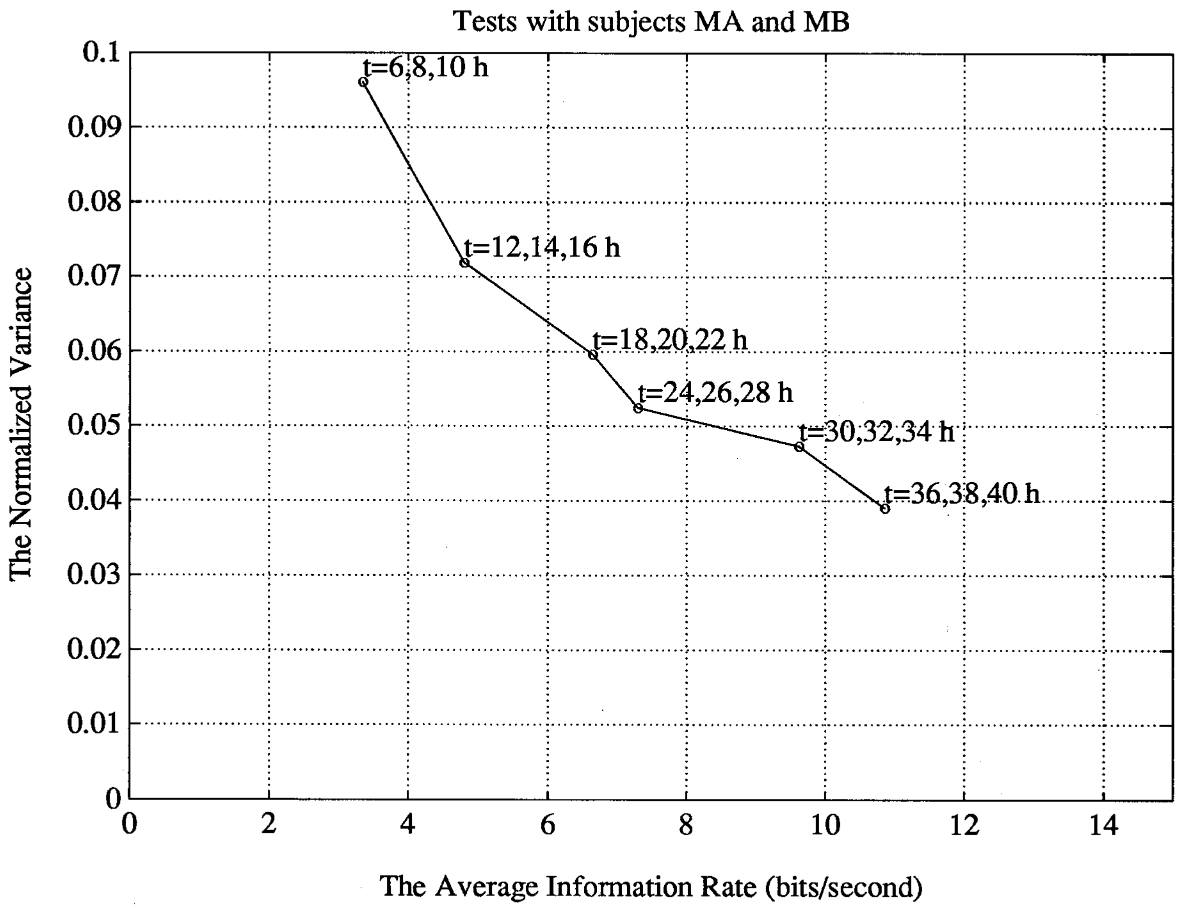

Figure 22 The Normalized Variance vs. The Average Information Rate with MCS

4.3.2 The MCS Keyboard Compared with the Standard Stenograph Boswell Keyboard

The experimental results indicate a clear performance advantage of the designed MCS keyboard over the group practising the standard stenograph Boswell keyboard. For comparison, figures for performance of the MCS and Boswell with blind and visually impaired subjects are depicted together in Figure 23.

The experiment shows that the time to memorize the hand positions for all the phonemes using MCS is short (2.5 to 11 hours) and the time to memorize the hand positions for all the phonemes using Boswell is long (more than 34 hours). This is because that subjects in MCS just needed to memorize 41 codes of MCS, which is much less than 259 codes of Boswell.

In the Boswell group, the typing rates, 25 WPM for BC at 85 h, 35 WPM for BD at 281h and 38 WPM for BE at 297h, are very low indeed when one considers the large training time involved. Their average rates of progress are positive, but a plateau is reached which is maintained for a periods exceeding 30 hours. Subject BA using the standard Boswell typed only 25 WPM at 50h and his rate of progress at this point was considerably slow too. In sharp contrast with Boswell group, at the end of MCS training, subjects MC and MD typed at an average level of 47 WPM at 50h and 39 WPM at 40h respectively and progress was still continuing at a fast pace.

The analysis of variance of typing rate differences between MC with MCS and BA with Boswell was highly significant, $F(1/4) = 12.65,\ \alpha < 0.01$.

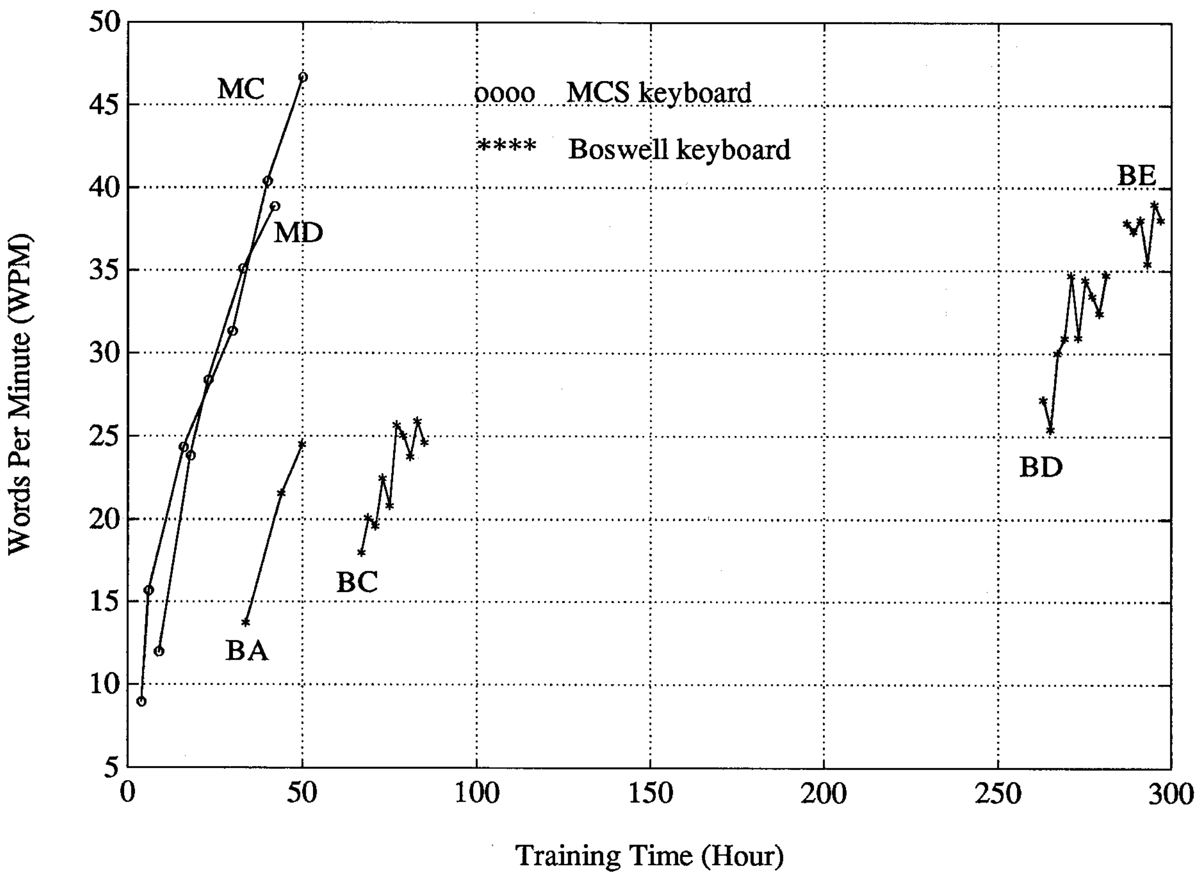

Figure 23 Performance of MCS Keyboard and Boswell Keyboard with Blind and Visually Impaired Subjects

4.3.3 The MCS Keyboard Compared with Gopher's Chord Keyboard

In order to compare the MCS' performance with Gopher's, we have used a vertical scale words per minute instead of characters per minute: 1 word=5.0 characters=3.1 phonemes. Figures for performance of Gopher's two-hand chord keyboard ([28]) and MCS keyboard are shown in Figure 24. For comparison, the MCS figures were obtained from the two sighted subjects.

Gopher's keyboard works with the 23 letters of the Hebrew alphabet, and in a matter of 35 hour training, 42 WPM can be obtained from a group consisting of 6 sighted subjects. The time to learn the finger movements for code was extremely short being less than an hour. Learning the alphabet of 23 letters is less of a task than the 41 phonemes, and is a reason why the latter took longer (neither learning time would seem to be unacceptable). Apart from this bias, the rates of progress seem much the same with the MCS giving equal performance at the end of the sessions. The analysis of variance of the difference of the typing rates between Gopher's keyboard and MCS keyboard did not reach the statistical significance, $F(1/14) = 0.0116$.

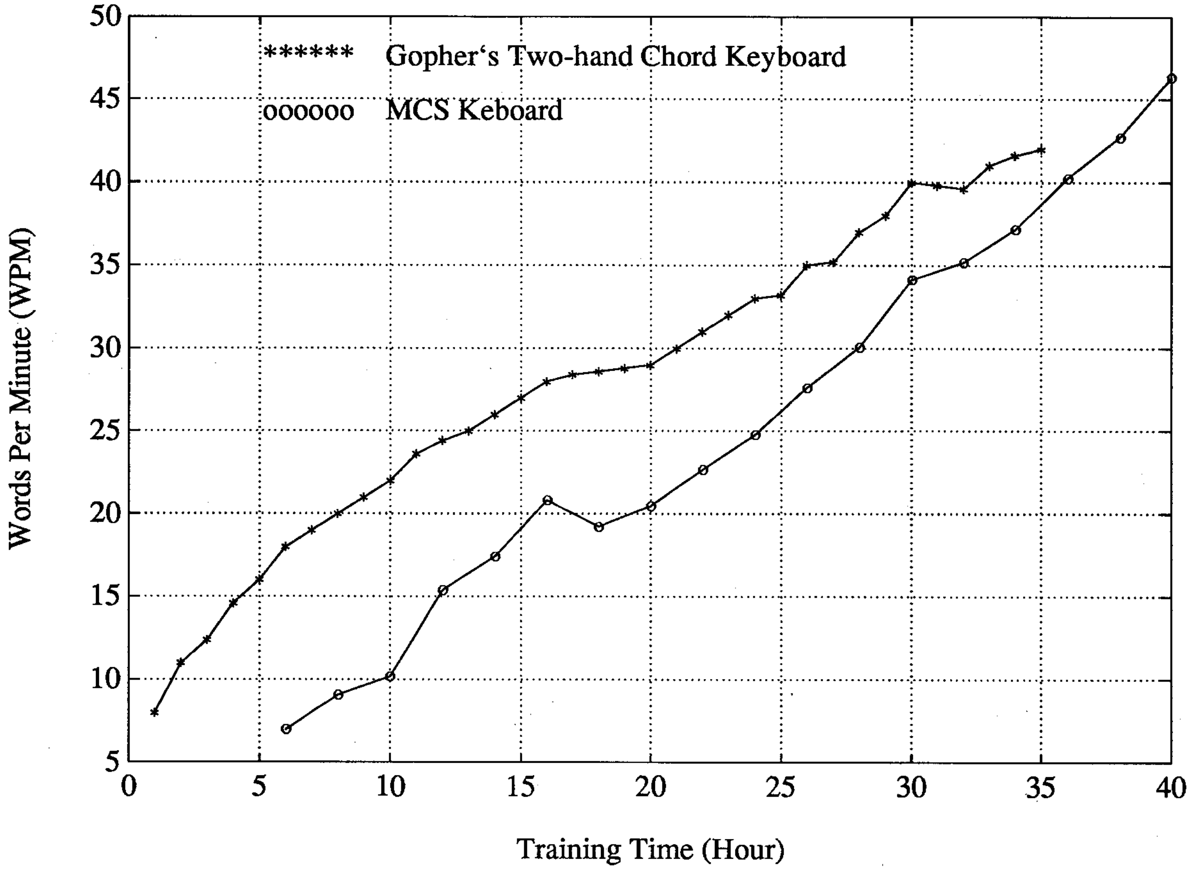

Figure 24 Performance of MCS Keyboard and Gopher's Two-hand Chord Keyboard with control Subjects

4.3.4 The MCS Keyboard Compared with QWERTY Keyboard

Compared with Gopher's experiment with QWERTY, MCS keyboard have significantly better performance than QWERTY keyboard. Figure 25 presents the Gopher's results on QWERTY and MCS with two control subjects.

Not surprisingly MCS subjects took 5 hours longer to learn the phoneme code than QWERTY subjects to learn the letter positions. However, at the end of training sessions MCS subjects typed at an average speed that was almost twice as fast as QWERTY subjects. More important, their rate of progress at this stage was two and half times larger. The analysis of variance of the difference of the typing rates between QWERTY keyboard and MCS keyboard is highly significant, $F(1/14) = 55.61,\ \alpha < 0.01$.

Subjects typing on the QWERTY are required to acquire fingers and hand trajectories, while such a requirement does not exist on the MCS keyboard. An important part of the touch typing skill is the ability to move hands and fingers along the required trajectories. For QWERTY and even with a limited set of 23 characters, the amount of travel and the number of different trajectories are quite large. Both features increase the load on motor coordination considerably. With the MCS, for most of the time, hands and fingers rest on their home keys.

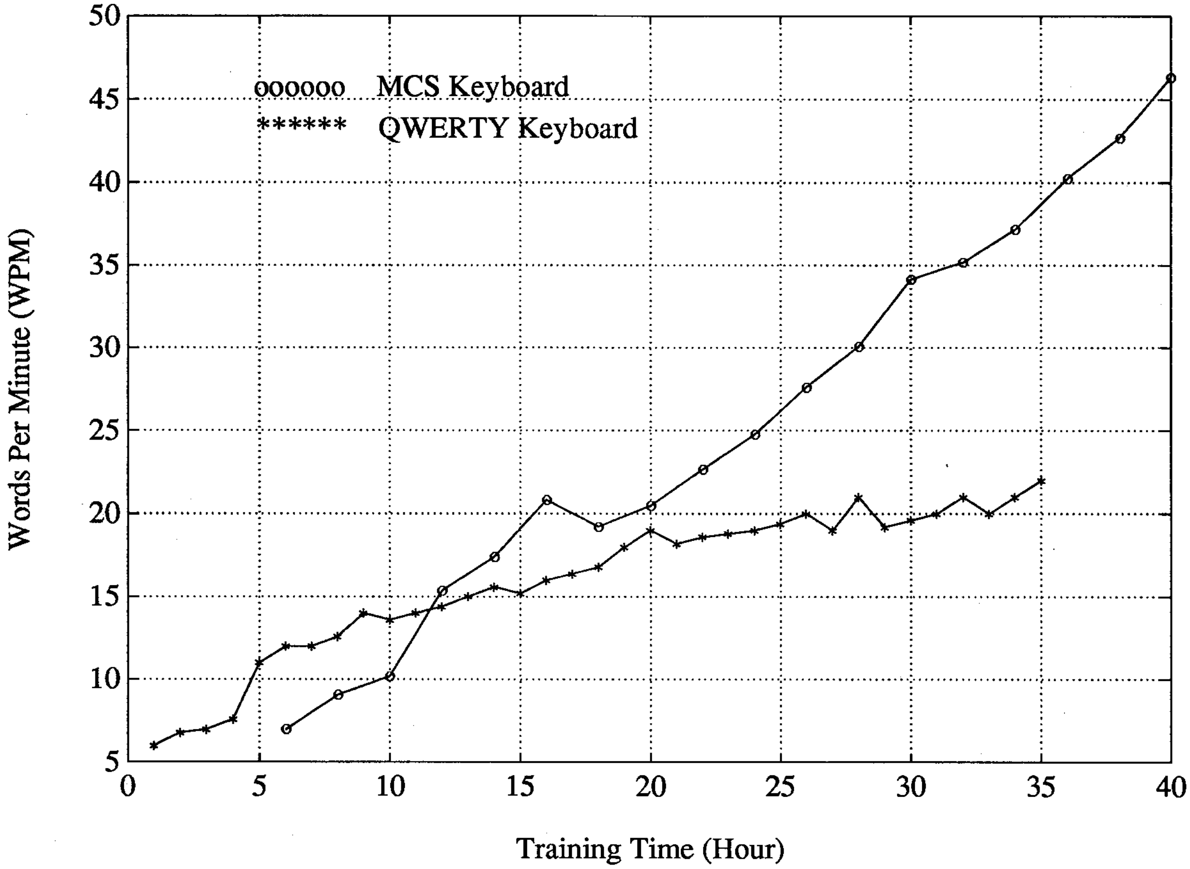

Figure 25 Performance of MCS Keyboard and QWERTY Keyboard with Sighted Subjects

With the QWERTY keyboard, the time needed to produce a keystroke is dependent on the specific context in which the character appears. Basically this means that the interkey interval for a given character is not constant, but varies as a function of the characters that precede it, and possibly those that follow it. Specific examples have been provided by Salthouse ([40]). He quotes the letter "o" in the "quick brown fox jumped over the lazy dog" typed by an expert typist; interstroke interval for "o" in the four positions were 370, 160, 185 msec and 130 msec ($\boldsymbol{m}$=211.25 msec, $\boldsymbol{s}$=108.20 msec, $\boldsymbol{s/m}$=0.5122) respectively. This is because the letter "o" is sometimes preceded by a keystroke on the alternate hand and sometimes by a keystroke on the same hand and the corresponding hand and finger trajectories are different, therefore there is "awkwardness" transfer from one movement to the next movement. In a well designed keyboard, we believe that interstroke interval ought to be constant. Compared with our results for subject MA shown in Figures 15 and 16, we see that the variations of the response times to the phonemes were getting less and less with training and all the ratios, $\boldsymbol{s/m}$, are less than 0.5122. It should be noted that the subject MA with MCS just got 40 h of training far less than that an expert typist would have with the QWERTY. Thus we conclude that the MCS keyboard suffers little from "awkwardness" transfer and is a well designed keyboard.

Chapter 5 Summary and Suggestion

5.1 Summary

This thesis deals with the design and testing of an experimental stenograph keyboard. Our objective is to overcome the problems encountered by the standard stenograph keyboards and to develop a new one which reduces learning time and increases operating speed.

The new keyboard layout, called the Minimum-Chord Stenograph (MCS), is presented. It is based on a number of rules. Some come from the literature of the normal QWERTY keyboard; others from the literature of the chord keyboard and the standard stenograph itself. The MCS keyboard comprises two panels of six keys, one for each hand. The fingers are generally above particular keys and each finger thus has only to move in one direction, up or down so that the relocation of the fingers is at a minimum. The phoneme is the basic input unit and is entered by pressing simultaneous combinations of keys. Mirror symmetry is used for right and left hands. The basic layout will allow exact phonemic descriptions of the text or speech to be entered by alternate hand typing.

A suboptimum coding for the MCS was developed. Phonemes were coded onto chord combinations such that the more frequently used phonemes were associated with easier chords. This was to ensure that the maximum information rate could be reached.

Experiments were carried out with MCS and the standard stenograph-Boswell. The implementation of the MCS was realized from a Boswell keyboard system by plugging in a special EPROM chip with the MCS coding. The time between successive movements of hands on the keyboards was precisely measured with a 386 computer.

The experimental results with support from the literature points to the following points:

1. The problem of training time for the stenograph in FP mode seems to be solved at least at the level of initial competence. The experiments show that the MCS keyboard enables fast initial acquisition, with all subjects able to memorize the hand positions for all the phonemes in less than 11 hours. This is much less than that (more than 34 hours) required for the standard stenograph-Boswell keyboard.
2. MCS' typing performance (words per minute) is better than standard Stenograph-Boswell. With the MCS, the learning curves of Figure 11 show a rapid increase of competence with training time. After a short training period, 40 to 50 hours, subjects could reach entry rates from 39 WPM to 52 WPM. At the end of training, the rate of progress was

still continuing at a fast pace. This is very encouraging. In contrast to the MCS, the stenograph-Boswell keyboard was much more difficult to learn. Figure 23 shows that subjects could only reach about 38 WPM after almost 300 hours of training. This is particularly unpromising considering the large amount of training the subjects had.

3. MCS' typing performance is significantly better than QWERTY's even though the MCS subjects took five hours longer to learn the MCS coding. As shown in Figure 25, at the end of training sessions, the MCS subjects typed at an average rate that was almost twice as fast as the QWERTY subjects. Another phenomenon which should be mentioned is that QWERTY's operation is much dependent on the specific context even with an expert typist (Salthouse, [38, 40]). With the MCS, the context phenomenon is much reduced with training as shown in Figures 15 and 16, and the smooth information flow is being uniformly approached as shown in Figure 22.
4. With MCS, the error rates fell with training shown in Figure 17. Most of the errors are attributed to motor deficiencies when typing multi-key clusters at high speed.
5. With MCS, all the subjects were satisfied with their performances at the end of training. They did not have any problems of breaking speech or words into phonemes. Some were very exited with the MCS when

their performances surpassed those with QWERTY. The skill of the latter had taken years for them to acquire.

6. The components of typing skill on the MCS keyboard are sufficiently remote from those involved in typing on QWERTY keyboard, to preclude major interference and transfer problems. Thus, a proficient typist can add this new skill to his/her arsenal without worry. Neophytes can be taught the new skills.

There are no rules for designing the stenograph keyboard, which is involved in complex perceptual, cognitive, linguistic and motoric processes. However, the MCS keyboard suggests promising directions for improving to performance of speech captioners and other assistive devices which require rapid and accurate input of language information to processors to aid the blind and adventitiously deafened people.

5.2 Suggestion

1. The utilization of special abbreviation codes with MCS keyboard can increase the information rate. However, it involves an additional set of trade-offs and compromises. They include frequency of usage of each abbreviation, number of keyboard strokes involved and/or the motor difficulty of the chord entry, and the size of the abbreviation vocabulary. Decisions with respect to these variables are certainly expected to affect throughput and training time, but the trade off functions are largely unknown. One possible method, however, is that one can systematically formalize the rules of abbreviation codes to reduce the training time.
2. The Stenograph keyboard presented here has speech output as well as print output. Justification of the speech is that it helps the novice. At high speed the speech output is generally ignored. Yet the speech ought to reinforce the operator telling him or her that the correct keys have indeed been pressed. The problems in this area have yet to be studied.

References

[1] R. I. Damper, "Speech technology — implications for biomedical engineering," *Journal of Medical Engineering and Technology*, vol. 6, no. 4, pp. 135–149, 1982.

[2] C. W. Heckathorne and D. S. Childress, "Applying anticipatory text selection in a writing aid for people with severe motor impairment," *Micro (IEEE)*, pp. 125–131, June 1983.

[3] A. Downton and A. Newell, "An assessment of palantype transcription as an aid for the deaf," *International Journal of Man-Machine Studies*, vol. 11, pp. 667–680, 1979.

[4] I. Beard, "Palantype reporters are helping the deaf," *National Shorthand Reporter*, vol. 44, no. 3, pp. 24–26, 1983.

[5] *Instant TV Captions for Deaf Begin Tonight.* San Jose Mercury: Associated Press, October 1982.

[6] M. P. Beddoes and Z. Hu, "State of the art with talking stenographs for the blind," in *Proceedings of the Sixth Annual Conference on "Technology and Persons with Disabilities"*, (Los Angeles, USA), March 20–23, 1991.

[7] A. F. Newell and P. R. Hutt, "Subtitling "live" television programmes for the hearing impaired," *International Journal of Man-Machine Studies*, vol. 11, pp. 693–699, 1979.

[8] G. Hayward, "A profoundly deaf businessman's views on the palantype speech transcription system," *International Journal of Man-Machine Studies*, vol. 11, pp. 711–715, 1979.

[9] R. G. Baker and A. F. Newell, "Simultaneous speech transcription and TV cations for the deaf," in *Processing of Visible Language* (P. A. Kolers, ed.), vol. 2, Plenum Publishing Corp., 1983.

[10]A. W. Booth and M. S. Barnden, "Voice input to English text output," *International Journal of Man-Machine Studies*, vol. 11, pp. 681–691, 1979.

[11]M. P. Beddoes, "Design features of a C-based software talking aid for the blind and handicapped called SPEECHEX," *IEEE Transactions on Biomedical Engineering*, vol. BME-33, no. 4, pp. 463–467, April 1986.

[12]M. P. Beddoes, "A talking stenograph for the blind," *IEEE Control Systems Magzine*, pp. 43–44, June 1989.

[13]J. L. Flanagan, "Talking with computers: Synthesis and recognition of speech by machines," *IEEE Transactions on Biomedical Engineering*, vol. BME-29, pp. 223–232, April 1982.

[14]H. P. Van Cott and R. G. Kinkade, *Human Engineering Guide to Equipment Design*. Washington, D. C.: U. S. Print House, 1972.

[15]A. Dvorak and G. C. Ford, *Typewriting Behavior*. New York: American Book Company, 1936.

[16]A. Dvorak, "There is a better typewriter keyboard," *National Business Education Quarterly*, vol. 12, no. 2, pp. 51–88, 1936.

[17]H. Yamada, "A historical study of typewriters and typing methods: from the position of planning Japanese parallels," *Journal of Information Processing*, vol. 2, pp. 175–202, 1980.

[18]R. T. Griffith, "The minimotion typewriter keyboard," *Journal of the Franklin Institute*, vol. 248, pp. 399–436, 1949.

[19]A. Martin, "A new keyboard layout," *Applied Ergonomics*, vol. 3, no. 1, pp. 48–51, 1978.

[20]K. E. Kroemer, "Human engineering the keyboard," *Human Factors*, vol. 14, pp. 51–63, 1972.

[21]D. Ferguson and J. Duncan, "Keyboard design and operating posture," *Ergonomics*, vol. 17, no. 6, pp. 731–744, 1974.

[22]L. G. Malt, "Keyboard design in the electronic era," in *PIRA Symposium, Developments in Data Capture and Photocomposition*, 1977.

[23]W. E. Cooper, *Cognitive Aspects of Skilled Typewriting*. Springer-Verlag, N. Y., 1983.

[24]J. L. Arnott, "A comparison of palantype and stenograph for use in a speech transcription aid for the deaf," *Journal of Biomedical Engineering*, vol. 1, pp. 201–210, 1979.

[25]J. L. Arnott, "A comparison of Palantype and Stenograph keyboards in high speed speech output systems," in *RESNA 10th Annual Conference*, (San Jose), 1987.

[26]E. T. Klemmer, "A ten-key typewriter," tech. rep., IBM Research Memo RC-65, Yorktown Heights, New York, 1958.

[27]G. R. Lockhead and E. T. Klemmer, "An evaluation of 8–key word writing typewriter," tech. rep., IBM Research Memo RC-180, Yorktown Heights, New York, 1959.

[28]D. Gopher and D. Raij, "Typing with a two-hand chord keyboard: will the QWERTY become obsolete?," *IEEE Trans. on Systems, Man, and Cybernetics*, vol. 18, no. 4, pp. 601–609, July/August 1988.

[29]R. D. Steel and S. L. Wood, "An efficient and versatile speech prosthesis," in *Digest of Paper's, Spring COMPCON 83*, (San Francisco, USA), pp. 34–38, Feb/March 1983.

[30]R. Kinkead, "Typing speed, keying rates and optimal keyboard layouts," in *Proceedings of the Human Factors Society Nineteenth Annual Meeting*, (Dallas, Texas, U.S.A.), pp. 159–161, October 1975.

[31]L. J. West, *Acquisition of Typewriting Skills*. second edition ed., 1983.

[32]*DECtalk: A Guide to Voice*. Digital Equipment Corporation, 1985.

[33]A. Gimson, *Introduction to the Phonology*. McGraw-Hill, Inc., 1989.

[34]R. E. Hayden, "The relative frequency of phonemes in general american english," *Word*, vol. 6, no. 6, pp. 217–223, 1950.

[35]P. B. Denes, "On the statistics of spoken English," *The Journal of the American Society of America*, vol. 46, no. 3, 1965.

[36]R. Seibel, "Performance on a five-finger chord keyboard," *Journal of Applied Psychology*, vol. 46, no. 3, pp. 165–169, 1962.

[37]N. Rochester and E. Sharp, "The chord keyboard," *Computer*, vol. 11, no. 12, pp. 57–63, 1978.

[38]T. Salthouse, "Perceptual, cognitive, and motoric aspects of transcription typing," *Psychological Bulletin*, vol. 99, no. 3, pp. 303–319, 1986.

[39]D. Gopher and W. Koening, "The representation of movement schemes in a long-term memory: lessons from the acquisition of a transcription skill," *Acta Psychologica*, vol. 60, pp. 105–134, 1985.

[40]T. Salthouse, "The skill of typing," *Scientific America*, vol. 250, pp. 128–136, 1984.

[41]J. Noyes, "The QWERTY keyboard: a review," *International Journal of Man-Machine Studies*, vol. 18, pp. 256–281, 1983.

[42]H. C. Ratz and D. K. Ritchi, "Operator performance on a chord keyboard," *Journal of Applied Psychology*, vol. 45, no. 5, pp. 303–308, 1961.

[43]R. Boff and J. P. Thomas, *Handbook of Perception and Human Performance*. New York: John Wiely, 1986.

[44]G. Keppel and S. Zedeck, *Data Analysis for Research Design: Analysis of Variance and Multiple Regression/Correlation Approaches*. W. H. Freeman and Company, 1989.

[45]J. Guilford and B. Fruchter, *Fundamental Statistics in Psychology and Education*. McGraw-Hill, Inc., 1978.

[46]R. Wardhaugh, *Introduction to Linguistics*. McGraw-Hill, Inc., 1972.