Keyboard design in the electronic era

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1 Introduction

'As technology advances it has tended to outstrip our appreciation of human needs in working situations, and lack of such knowledge has led to the design of machinery ill-fitted to human operation.' - (Grandjean[1]).

One piece of equipment which is universally recognised as being ill-fitted to human operation is the ubiquitous typewriter keyboard. The standard Sholes-designed keyboard with its qwerty letter layout, must be one of the very few pieces of equipment which has entirely resisted improvements, which could and should have been made to complement our advancing technological ability.

It has been said of the Sholes letter layout that it would probably have been chosen if the objective was to find the least efficient—in terms of learning time and speed achievable—and the most error producing character arrangement. This is not surprising when one considers that a team of people spent one year developing this layout so that it should provide the greatest inhibition to fast keying. This was no Machiavellian plot, but necessary because the mechanism of the early typewriters required slow operation.

As the qwerty layout and design have been retained in their entirety on electric and electronic keyboards which have faster keystroke capacity, it is not surprising that keying speed did not improve significantly when mechanical keyboards were replaced by electric and electronic equipment. The *Guinness Book of Records* reports these world speed records:

1918 on a Standard Underwood for one minute only 170 wpm (net)
1946 on an IBM Electric for one minute only 216 wpm (net)
An increase of 27.06%.

This increase is, however, only maintained on a one minute test as the records for one hour tests show:

1923 on a Standard Underwood for one hour 147 wpm (net)
1941 on an IBM Electric for one hour 149 wpm (net)
An increase of 1.36%.

Higher speeds could well have been expected as keying speeds for equipment increased from 11 kps for standard mechanical typewriters to 18 kps for electric and 35-50 kps for electronic. Restraints no longer exist in the mechanism of the hardware and must be looked for in other factors.

With greater use of computer aided technology, it becomes increasingly apparent that the cost of maintaining the standard qwerty keyboard design and layout is too great for developed societies to tolerate. The costs are both indirect and direct. Indirect costs arise from the ill-health suffered by the increasing number of people now using keyboards. Direct costs are in the acknowledged 'bottleneck' in keyboard input, whether in print production or in any form of typewriting or data-input, and in the length of training time required.

2 Indirect costs

Manufacturers of keyboards, and others, have claimed that the design of the keyboard is not important, as the human body can accustom itself to the required positions. Equally it has been claimed that although the human body can and does accustom itself to poor design, this is always done at a cost. The cost in terms of human suffering is dramatically evidenced by the research done by Ferguson and Duncan[2], by Osanai[3] and others before them.

Ferguson and Duncan have given a detailed diagnosis of the physical ill effects of the design of keyboards. Their investigations produced clinical evidence of finger, wrist and shoulder joints of keyboard operators with marked flexion, extension, abduction and deviation due to keying continuously on keys which force these joints into unnatural positions. Osanai gives evidence of pains in neck, shoulder, arms, hand and back, which seem to have been caused by repetitive quick motions of the hand and fingers as well as by the static muscular tension required to sustain working posture. He also isolated hardening of the muscles and tenderness.

Apart from such detailed clinical research studies, physiotherapists and osteopaths observe that keyboard operators provide them with a large occupational patient group.

Already millions of people all over the world use keyboards: typists in offices; students in schools, colleges and universities; in data preparation departments; airports; police offices and, of course, in newspapers and printing. They may produce characters on paper; paper or magnetic tape; disc;

on a visual display screen; direct to a computer: even if they use an adding machine or calculator they are still keyboard operators. Futurologists predict that the number of people who use keyboards will increase quite dramatically in the next few decades. More and more information is being fed into computer store. Here in Britain the Post Office is currently considering a scheme for putting one whole encyclopaedia into computer store for reference through code dialling. Before the year 2000 AD children at school may well learn to type before they learn to write. The advantages for children have already been proved (Wood and Freeman[4]: Moore and Anderson[5]).

If more and more people use keyboards and if they start to use them at an earlier age when physical defects may be more readily induced, the cost in terms of human suffering will increase unless the design of the keyboard is changed.

3 Direct costs

The most direct cost is seen in low rates of production and inaccuracy. Training costs are higher than they need be because of the time required to gain proficiency and the complexity of the training programmes which alone produce high speed, accurate operators.

The story is told that at least one publisher anticipated keyboard input speed equal to the kps capacity of the equipment that had been purchased for his newspaper. At 18 kps this would be 180 wpm or 64 800 kph.

The 'bottleneck' of keyboard input is readily apparent in figures quoted for a variety of keyboard operations:

a
average production for newspaper production on hot metal Linotype machines was 3 lines of 31 characters per minute. Currently in the industry using qwerty layout machines a figure of 7000-10 000 kph is quoted.
b
in offices in England, 15 wpm, 5400 kph is given as an average for transcripton from shorthand notes to typescript (Whittle[6]).
c
in America a conducted cyclometer measure of typing output in terms of keystrokes recorded that so-called full-time typists produced less than two hours of typing per eight-hour day, against a measure of 83 kpm, ie 13.83 wpm, 4 980 kph (Lannon[7]).

In the newspaper industry attempts to break the keyboard input 'bottleneck' have mainly been concentrated on eliminating tasks and so reducing the requirement for keyboarding. This has been done through the use of Optical Character Recognition (OCR) systems for wire services and classified advertising: front desk systems for editorial: and computer store and retrieval for repeat and updating. All these methods have involved high capital investment in electronic equipment and change of skill and tasks for many of the people involved. These expensive and extensive innovations have been implemented whilst the qwerty keyboard with its inhibiting design and layout have been retained.

However many tasks are eliminated, and it does make sense to eliminate re-keyboarding of any kind, there remains the initial keyboard input which is still subject to the 'bottleneck' caused not only by low operating speeds but by the high error rate inherent in the qwerty keyboard.

The fact that almost anyone can learn to type at up to 20 wpm (7200 kph) by almost any method, obscures the fact that it takes skilled training and high dedication on the part of operators to reach speeds of over 80 wpm (28 800 kph), which alone make sense of the high capital investment in keyboard systems both in newspapers and print and in offices generally.

The uneven stretches caused by the diagonal slope of the rows of keys on qwerty result in uneven reach and distance movements, and this together with the letter layout which reinforces language confusions and induces errors, adds to learning difficulties and training time. Of course there are many highly skilled and accurate keyboard operators. They are only a small proportion of the total number of people who learn to use a keyboard and their skill has taken longer to achieve and required greater effort. These difficulties all add to the cost of providing training both in our educational and training establishments, and in industry.

'All plans come apart at the seams unless input problems are resolved by operators whose native talents are not restrained or limited by the keyboard systems. When planning a system, give at least as much consideration to the selection of the keyboards and training of the operators as to the processing rate capabilities of the phototypesetter and the computer' (Kneller[8]). This was written in 1971 and the advice still holds true.

4 Effect of keyboard design

If we accept the evidence that the Sholes keyboard design forces fingers into such unnatural positions that physical malformations are caused, it is obvious that keying speeds cannot be optimal.

One simple way of assessing the effect of fingers having to make unnatural stretches to fit a flat horizontal home row is to compare the speed of two fingered lateral keying with two fingered contra-lateral keying. Table 1 shows average kps rates for 10 experienced operators, five keying on electric and five on mechanical keyboards, for two-fingered adjacent lateral keying.

The losses in speed from fastest to slowest are: 42.36% on electrical and 39.78% on mechanical.

Table 2 gives average kps rates for the same operators for two-fingered contra-lateral keying.

The losses in speed from fastest to slowest are: 3.91% on electrical and 11.83% on mechanical.

It has been fairly generally accepted that the reason for such differences in lateral keying speed was the relative strengths and weaknesses of fingers. But this

	Left hand			Right hand			
Fingers*	1/2	2/3	3/4	3/4	2/3	1/2	% decrease fastest to slowest
Letters	as	sd	df	jk	kl	l;	
Electric	6.34	7.84	9.08	11.00	8.24	6.64	jk – as = 42.36%
Mechanical	3.46	3.80	4.74	5.58	3.66	3.36	jk – l; = 39.78%

*Numbers for fingers: 1 = little fingers: 2 = ring fingers: 3 = middle fingers: 4 = index fingers.

Table 1
Ten second keying of two fingered adjacent lateral sequences, in kps.
Average kps rate for ten experienced keyboard operators, 5 on electric: 5 on mechanical keyboards

Fingers	1	2	3	4	
Letters	a;	sl	dk	fj	% decrease fastest to slowest
Electric	10.32	10.32	10.74	10.62	dk – a; = 3.91%
Mechanical	7.90	8.50	8.96	8.78	dk – a; = 11.83%

Table 2
Ten second keying of two fingered contra-lateral sequences, in kps.
Average kps rate for ten experienced keyboard operators.

			Operator 1		Operator 2	
			Keyboards			
Fingers	Sequence	Letters	Mechanical	Electric	Mechanical	Electric
rh 4/3	lateral	jk	5.2	9.8	6.2	9.0
3/3	contra-lateral	dk	10.1	9.6	7.2	8.5

Table 3
Ten second keying on fastest two-key lateral (jk) and fastest two-key contra-lateral (dk).
Average kps rate for two experienced operators, each operator on both mechanical and electric keyboards

reason cannot be accepted if we compare the speed for contra-lateral keying. Slow lateral keying on the ring and little fingers cannot be due entirely to the relative strength or weakness of the fingers.

If strength of fingers is measured in terms of contra-lateral keying speed then lateral keying speeds might be expected to be an average of contra-lateral of two adjacent fingers. That this is not so is obvious from the figures given in Tables 1 and 2. The inhibition on lateral keying speed must be due to some factor other than finger strength, and it becomes very obvious when watching operators keying these tests that the inhibition is caused by unequal finger lengths. The awkward stretch and lift positions which are maintained by the little and ring fingers (1/2) in lateral keying are very apparent and must account largely for the sharp fall in keying rate. This is particularly so on mechanical keyboards where the depth of depression is greater than on electric keyboards and where some force is required.

Although electric keyboards have been in wide general use for at least 20 years the most frequently quoted statistics for speed of finger operation on keyboards are based on tests done on standard mechanical keyboards. These statistics show that all contra-lateral keying is faster than all lateral keying. Whilst undoubtedly true for early models of mechanical typewriters, it is not true for keyboards now in general use. Tables 1 and 2 show this and Tables 3 and 4 give figures for two operators each keying on a manual and on an electric keyboard.

Operator 1 had used a standard typewriter almost continuously for 24 years and this was a first attempt to use an electric typewriter. Operator 2 had used typewriters for more than 40 years—35 years on mechanical and then five years on electric.

Table 3 compares kps rates on two-key lateral and contra-lateral sequences and Table 4 gives kps rates for four-key lateral and contra-lateral sequences.

		Operator 1		Operator 2	
		Keyboards			
Sequence	Letters	Mechan-ical	Electric	Mechan-ical	Electric
Inward lateral	asdf;lkj	5.4	6.6	6.0	11.4
contra-lateral	a;sldkfj	5.5	6.4	7.0	7.6
Outward lateral	fdsajkl;	5.0	5.1	5.6	10.6
contra-lateral	fjdksla;	4.8	4.4	7.7	7.7

Table 4
Ten second keying on four-fingered inward lateral, outward lateral and contra-lateral sequences.
Average kps rate for two experienced operators, each operator on both mechanical and electric keyboards.

These lateral sequences are all keyed faster than the contra-laterals. Even Operator 1 who had never used an electric machine before was able to achieve higher speeds on contra-laterals.

The fact that lateral keying is faster is important in considerations for letter layout. If letter layout provides for high use of lateral keying, speed and accuracy will be increased.

Table 5 gives detailed results for 20 operators in four groups of five. Two groups keyed on electric and two groups on mechanical. Two groups were experienced operators, one group had been in training for six weeks at a technical college, and one group had had no keying experience of any kind.

These figures confirm results already given in Tables 1-4 and provide much useful information for determining optimum letter layout. They also raise some as yet unanswered questions.

5 New design for keyboards

If we accept that the constraints of forcing fingers of unequal lengths to key on a horizontal plane reduce speed, cause errors and human suffering, then it seems logical to think that key heights should fit the length of the fingers. This would provide for greatest ease and speed of finger movements. To support this suggestion, Ferguson and Duncan report that there is neither extension nor flexion of middle fingers.
As the middle fingers are the longest, they are naturally less distorted in their keying positions, and not surprisingly the Tables above show that these are the fingers which are the fastest on contra-lateral keying. If key heights are varied to fit the lengths of fingers, it is possible that extensions and flexions could be avoided for all the fingers. Key heights may also be varied to fit stretch positions for the index and little fingers which key six keys on two vertical rows. If the key-tops on the outside rows are tilted to meet the fingers the stretches would be reduced.

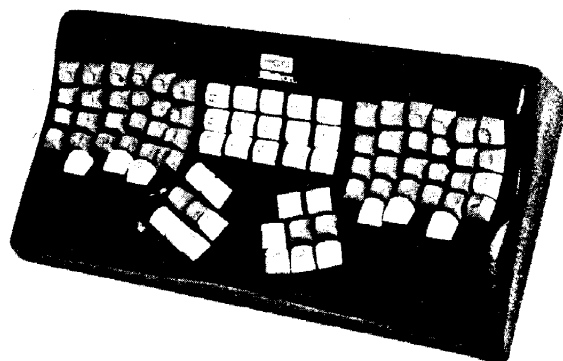These suggestions have now been given physical shape in the PCD-Maltron keyboard shown in figure 1.

Fig 1
PCD-Maltron keyboard with Maltron Mark II letter layout and control keys for print production

There are many advantages to this shaped-to-the-finger keyboard design which is also separated in the centre to eliminate wrist, arm and shoulder deviations and to provide space for up to eight keys for each thumb. Adjusting key height and slope to fit fingers rather than forcing fingers to stretch to keys, has the potential of providing considerable speed increase, even if only by raising the speed of all lateral keying. Through reduction of fatigue, higher speeds will be maintained for longer periods.

Training will become easier and higher keying levels will be attained by more aspirant operators, just because fingers are relieved of keyboard constraints. Because key heights vary for each finger, the kinesthetic sense of reach and distance which is essential for high speed touch keying will be learned with greater ease as fingers will readily sense they are not resting on their own keys. There will be no possibility of two fingered operation because of the fit of the keys to the fingers. In addition to fingers sensing their own keys, uneven and difficult stretches are eliminated and the combined effect makes it easier to be accurate.

Both left and right thumbs may now be used quite extensively. These two digits are the strongest and most flexible of all and have the back-up of a considerably larger section of the brain than other digits. Nine times the brain size in fact.

Table 5

Results of ten second keying of lateral and contra-lateral sequences on 'qwerty' keyboards. Mechanical and electric.
20 operators: all right handed: 6 male 14 female. Group 1: Experienced, Group 2: No keyboard experience, Group 3: Experienced, Group 4: After 6 weeks' training.

Fingers	Letters	Electric keyboards Group 1						Group 2						Mechanical keyboards Group 3						Group 4					
		*A	B	C	D	E	Av. kps	F	G	H	J	K	Av. kps	L	M	N	P	R	Av. kps	S	T	U	V	W	Av. kps
Lateral left hand 1/2	as	87	61	56	54	59	6.34	61	23	60	60	60	5.28	32	26	31	45	39	3.46	35	38	38	32	41	3.68
2/3	sd	105	87	64	68	68	7.84	61	57	58	55	58	5.78	38	23	31	54	44	3.80	48	38	43	38	43	4.20
3/4	df	126	85	72	102	69	9.08	63	59	60	59	58	5.98	48	38	38	59	54	4.74	54	50	62	47	51	5.28
right hand 1/2	;l	87	69	65	51	60	6.64	38	30	30	34	53	3.70	48	22	23	45	30	3.36	36	38	42	34	38	3.76
2/3	lk	113	87	69	69	74	8.24	66	60	62	70	81	6.78	39	21	33	51	39	3.66	48	46	46	37	41	4.36
3/4	kj	139	107	90	116	98	11.00	77	108	138	91	88	10.04	50	32	40	90	67	5.58	65	54	53	52	61	5.70
Ea. op. Av. kps		10.9	8.3	6.9	7.7	7.1		6.1	5.6	6.8	6.1	6.6		4.2	2.7	3.3	5.7	4.6		4.8	4.4	4.7	4.0	4.6	
Contra-lateral 1/1	a;	127	107	88	98	96	10.32	74	85	75	88	82	8.08	72	67	67	102	87	7.90	90	67	87	67	76	7.92
2/2	sl	115	113	83	109	96	10.32	81	85	80	87	81	8.28	83	65	71	111	95	8.50	104	76	95	65	74	8.28
3/3	dk	131	114	85	111	96	10.74	68	90	101	88	75	8.44	90	62	78	116	102	8.96	118	82	98	92	97	9.74
4/4	fj	126	104	89	116	96	10.62	71	86	81	89	84	8.22	85	68	75	111	100	8.78	110	81	87	95	88	9.22
Ea. op. Av. kps		12.5	10.9	8.6	10.9	9.6		7.3	8.7	8.4	8.8	8.1		8.3	6.6	7.3	11.0	9.6		10.8	7.7	9.2	8.0	8.4	
Lateral	asdf;lkj	126	104	114	71	66	9.62	32	25	31	27	61	3.52	40	–	38	55	48	4.53	46	43	51	40	45	4.50
	fdsajkl;	94	113	106	80	51	8.88	37	32	32	29	55	3.70	45	32	33	48	29	3.74	40	43	52	41	39	4.30
Contra-lateral	a;sldkfj	118	89	76	59	64	8.12	33	16	23	22	49	2.86	–	36	56	51	67	5.25	55	40	64	31	35	4.50
	fjdksla;	120	101	77	63	44	8.10	31	26	34	24	48	3.26	57	35	44	60	43	4.78	57	47	55	53	43	5.10

*Operators designated by alpha letters.

Manufactured by PCD Limited of Farnborough, Hants, England, the PCD-Maltron keyboards all have the facility for being used with either the qwerty layout, or the Maltron Mark II layout. Either may be accessed at the touch of a key.

6 Letter layout

Siting characters on the keys is a complex matter, and to arrive at an optimum layout many variables require consideration: motion economy principles related to hand and finger movements; finger strength and flexibility; the human neuromuscular structure. All these factors are included, as well as language restraints, such as letter confusions which result in common spelling errors and then appear as common keying errors, and allowance for statistical frequency of letters, single and in combinations of di- and tri-graphs, especially those in the commonest words. For high speed keying, it is necessary to:

a
balance the load between the two hands—making some allowance for right hand dominance

b
balance the load between the fingers—allowing for individual finger capacity

c
reduce finger movements to a minimum—by placing the most commonly used letters directly under the ten digits

d
reduce difficult finger motions to a minimum—reduce hurdles and stretches and avoid use of the same finger twice in succession

e
allow for fastest finger movements to be used most frequently—provide for lateral as well as contra-lateral keying

f
avoid long sequences on one hand—balance lateral with contra-lateral keying.

For accurate keying and for ease of learning, letter layout should take account of cybernetic requirements related to language. Highest source of error in reading and in spelling is located in vowels and vowel graphemes. On the qwerty layout the highest source of error is on the vowels *e* and *i*. On the Linotype layout it is on the vowels *a i o* and Dvorak[9] himself detected that of 3 329 errors analysed for the 'Simplified' keyboard 1 631 involved the vowels. The five vowel keys accounted for 48.99% of the errors analysed. (Figures abstracted from chart on p 504) If vowels are strategically placed so that they do not appear on adjacent keys, nor on the same finger and same row of the two hands, neural confusion may be avoided. This would provide the best possibility for accurate keying.

The factors cited above apply equally to English and to the other languages using the Latin characters. The order of frequency of use of alpha characters in these languages do not differ greatly. French, Spanish and Italian keying will be aided by correct placing of vowels, and Dutch and German which often have three or more consonants together will also benefit.

The degree to which these requirements can be provided for in a letter layout may be judged from the accompanying tables for the Maltron Mark II layout.

All these calculations are based on letter frequencies in 1013232 words—a total of 5930220 keystrokes including spaces and most used punctuation (Kucera[10]). Calculations are also given for letters in the 100 commonest words, which occur 481200 times within the 1013232 words, a total of 1871000 keystrokes.

Statistics for Maltron Mark II letter layout with comparative figures for Sholes (qwerty) and Dvorak (DSK) keyboards are given in the Tables below.

Table 6 gives the percentage of letters keyed on the home row for all the words analysed in the Kucera Corpus (all language) and for all the letters in the 100 commonest words in the Corpus.

Table 7 gives figures for single finger keying twice in succession and a separate list for single finger hurdles. Hurdles occur when a finger is required to key across the home row, from top to bottom alpha character row or from bottom to top row. They are the slowest movements because of the distance between the keys.

Table 8 gives figures for index finger stretches inwards to the centre rows of keys. (qwerty letters are *t g b* for left index finger, and *y h n* for the right index finger.) These are the most uneven stretches on the Sholes design and with vowels are a high cause of error. On the PCD—Maltron design the stretches are even and smaller, as well as being considerably fewer in number.

Table 9 gives percentage figures for balance of keying to each hand. Two sets of figures are given. The first set is for letters and punctuation keyed by the eight fingers only. The second set is for letters, punctuation and the space bar keyed by all ten digits for PCD—Maltron and nine digits for Sholes and Dvorak which do not use the left thumb.

Table 10 gives the balance of keystrokes to the fingers and thumbs of each hand. The use of the left thumb on the PCD—Maltron reduces the load to other fingers. This factor is chiefly responsible for the reduction of single finger used twice in succession and hurdles on the PCD—Maltron.

Statistically the Matron Mark II layout makes good sense. Cybernetically related to language frequencies, its degree of fit is already apparent in the ease with which learners are able to locate letters of the alphabet and key alphabetical sentences.

7 Implementing the changeover

Of course it will not be necessary for all keyboard operators to change to both the new design and the new layout. There is no reason why it should be mandatory as was the change to drive on the right side of the road in Sweden, or the change to decimal currency. A change can be made to the new design only, and for many operators this may be of sufficient

	All language %	100 commonest words %
Qwerty	43.62	51.88
Dvorak	73.31	86.25
Maltron Mark II	77.89	90.52

Table 6
Allocation of most frequently used letters to home row keys. Percentage
of letters keyed on the home row.

	Single finger keying twice in succession	Single finger hurdles
Qwerty	273 450	82 200
Dvorak	83 700	3 474
Maltron Mark II	24 826	321

Table 7
Number of occurrences of single finger keying twice in succession and of
hurdles. All language.

	Left index finger %	Right index finger %
Qwerty	12.27	13.73
Dvorak	9.33	7.52
Maltron Mark II	4.90	5.50

Table 8
Percentage of index finger stretches to centre keys. All language.

	Eight fingers only		Fingers and thumbs	
	Left hand %	Right hand %	Left hand %	Right hand %
Qwerty	57.03	42.97	47.35	52.65
Dvorak	44.51	55.49	36.95	63.05
Maltron Mark II	48.76	51.23	46.00	54.00

Table 9
Balance of keystrokes to each hand. Percentage of all language.

	Left hand					Right hand				
Fingers	1	2	3	4	Th	Th	4	3	2	1
Qwerty	6.7	7.2	15.7	17.75	—	17.0	15.7	7.5	10.3	2.15
Dvorak	6.75	7.2	11.0	12.00	—	17.0	14.15	11.4	11.4	9.10
Maltron Mark II	7.7	7.35	7.3	12.75	10.9	17.0	14.9	7.0	6.6	8.50

Table 10
Balance of keystrokes to fingers and thumbs. All language including most used punctuation and space bar.

benefit. The PCD—Maltron keyboard allows operators to use it with either the qwerty letter layout, or with the Maltron Mark II letter layout as they wish. The changeover to the new design can be made quickly and easily and requires only from five to 10 hours' practice. High speed operators who have tried this have said that this changeover is easier than moving from a standard typewriter to an electric one. The index fingers have most relearning to do because the awkward and uneven stretches to the centre rows have been eliminated.

Fig 2
PCD-Maltron keyboard with mag tape output and visual display unit

Changing to the new design only, will eliminate physical discomfort and will allow for increased lateral keying speed—where the qwerty letter layout permits of lateral keying. An increase of around 25% in keying speed may be anticipated.

Learning to operate a keyboard with a new layout does present more difficulty—or rather it does require more practice. It is very like learning to speak a second language. The quickest way to do this is not to speak the first language at all. But that is not the only way and most people who speak more than one language have learned to do so whilst still speaking a first language. Many thousands of Linotype operators who have learned to operate qwerty while still operating on the Linotype layout can testify to this. This makes it possible for operators to spend several hours a day learning the new keyboard language, while still producing on the qwerty machines.

Because the Maltron Mark II layout fits language requirements and has relatively few slow and difficult movements, it seems to be easy to learn. The first

Maltron Mark II layout appeared on a keyboard on 19 May, 1977 and there are at the time of presenting this paper for printing, no figures available for completed training. If the statistics are anything to go by, high keying speeds with high accuracy should be attained in relatively short training times.

8 Conclusion

There are two main reasons why the developments in keyboard design and layout described in this paper could not all have been made before the electronic era. It is only very recently that the technology has made it possible to fit a keyboard with the irregular shape of the PCD—Maltron. The equipment required to permit the flexible interchange from one keyboard layout to another is also very new. Great credit is due to Stephen Hobday of PCD Limited for seeing the possibilities and using them so inventively. In addition, computer printouts for language analysis make it possible to search and sort in months rather than in years.

It remains to be seen whether the massive keyboard population will take advantage of these technological developments in the short term, rather than in the long term.

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