The Standard and Dvorak Keyboards Revisited: Direct Measures of Speed

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ABSTRACT

The Dvorak keyboard has been claimed to be greatly superior to the standard typewriter keyboard. However, none of the earlier research on the relative merits of the two keyboards provided unconfounded measures, ones permitting attribution of the results solely to the differences between the keyboards. The present research supplied, for the first time, direct measures of speed on the two keyboards by the same persons. Eight experienced standard-keyboard typists, ranging in skill from the median speed of terminal high school trainees to beyond the 97th percentile speed of experienced employees (45-81 words per minute), typed high-frequency digraphs on both keyboards, resulting in a 4.0% superiority for the Dvorak keyboard. The relationship of present digraph findings to performance of realistic tasks is discussed, and research on whether differences in keyboard efficiency vary with the skill level of operators is recommended.

Under procedures that produced results entirely attributable to the keyboard designs, free of confounding factors, the Dvorak typewriter keyboard was found to produce speeds of keying 4.0 percent faster than those of the Standard (Qwerty) keyboard. However, employers were reported to be unwilling to bear the costs of the several weeks required to retrain employees on the novel keyboard.

KEYWORDS: keyboards, typewriters, Dvorak, QWERTY

NOTES

"The Standard and Dvorak Keyboards Revisited: Direct Measures of Speed" by Leonard J. West is an unusual paper to appear in the Santa Fe Institute Working Paper Series. The paper was written for researchers in vocational education rather than economists per se. What makes this paper important to the SFI Economics community is its focus on what has become one of the canonical examples of path dependence in economics, namely, the relative efficiency of the standard typewriter keyboard versus available competitors. As Brian Arthur discusses in the introduction to his Increasing Returns and Path Dependence in the Economy, the near universal adoption of the QWERTY keyboard when a more efficient alternative, the Dvorak, existed, played an important role in the development of his thinking on path dependence in the early 1980's. Paul David's "Clio and the Economics of QWERTY" (American Economic Review 1985) has become a standard empirical citation in the path dependence literature. Consequently, recent attacks on the importance of path dependence in understanding the economy have to some extent been based on claims that the QWERTY keyboard is actually more efficient than the Dvorak alternative. Professor West's paper is an interesting and all too rare effort at research which directly explores this issue, and provides evidence in support of the view that path dependence can lead to various inefficiencies in the economy.

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This research was aimed at identifying the more efficient (speedier) keyboard for personal and vocational use. However, the February 25, 1998 article in the Wall Street Journal (pp. B1 and B6) makes evident the relevance of keyboard data to market economics and, therefore, to economists.

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INTRODUCTION

Personal and occupational use of typewriter-like keyboards engages tens of millions of persons in the United States alone. The "Standard" (Qwerty) keyboard was first marketed in 1874 and has been the dominant one since the 1890s. Its major competitor since it was patented in 1932 is August Dvorak's "Simplified" keyboard, for which claims of substantial superiority over the standard keyboard have been made. However, none of the research on the relative efficiencies (speeds) of the two keyboards has produced outcomes attributable solely to the different arrangement of keys on the two keyboards. Also, some of the research used surrogate, rather than direct, measures of speed.

The vast investment in keyboard operation makes it desirable to identify which of the two keyboards is the faster, more productive one. To that end, the research reported here provides outcomes that can be attributed to the difference between the keyboard layouts, unconfounded by other variables. As well, the central and unique element of the research procedures permits comparing a familiar keyboard layout with any other layout that may appear in the future. The question is a practical, not a hypothetical or theoretical one, and a practical answer is sought.

Some History to Date

The rationale underlying the Dvorak keyboard was based on the time-and-motion studies of Taylor and the Gilbreths early in this century. The layout of its keys (in contrast to the standard-keyboard layout) was aimed at (1) more suitable hand, finger, and row “loads” (i.e., the percentage of the work done by each hand, each finger, and on each of the three alphabet rows) in typing English prose—taking letter and letter-sequence frequencies into account, at (2) maximizing the capacity for overlapping finger motions, and (3) in general, at reducing finger-movement distances, thereby permitting faster speeds. Indeed, lesser finger-movement distances was the feature most heavily emphasized by protagonists for the Dvorak keyboard as accounting for its superiority over the standard keyboard. The measurement of finger-movement distances (in various ways) was a frequent target of research. From those measures, estimates of probable differences in speed were sometimes made. Not seldom, percentage differences in movement distances were (impermissibly) assumed to equal percentage differences in speed, resulting in grossly exaggerated claims of superiority for the Dvorak keyboard.

Research reviews. The simplified keyboard has had a long and checkered history to date. Yamada (1980) supplied an extensive account of the claims for, and research on, that keyboard from its earliest years. A selectively updated review (Ober, 1992) included mention of exaggerated claims for the Dvorak keyboard as well as reservations about the quality of the early research on that keyboard as such, as well as in relation to the standard keyboard.

Some of the claims rest on anecdotal evidence, such as prizes won by Dvorak typists in international contests. In other instances, Dvorak trainees usually outperformed standard-keyboard trainees in pedagogical environments--by 15% to 20% in short timings and by 25% to 50% in realistic typing tasks, according to Yamada (1980, p. 185). There are indications, however, of differences in teaching skill; the Dvorak instruction was often conducted by highly credentialed persons with up-to-date, sophisticated knowledge of learning processes. Research that involved retraining of experienced standard-keyboard typists on the Dvorak keyboard also suffered from deficiencies in design or in the implementation of the design--such as varying and unequal numbers of hours devoted to the retraining.

Nonetheless, despite the uncertain reliability of the estimates of the extent of superiority of the Dvorak keyboard, the rationale underlying the layout of its keys makes its superiority highly likely.

Assuming work of acceptable quality, the only valid criterion of efficiency is speed. Can one do faster work on keyboard X than on keyboard Y? There have never been, however, any experimental comparisons of actual performance on the two keyboards that exercised suitable control over potentially confounding factors (e.g., identical concepts underlying the training materials and procedures, equivalent skill in conducting the instruction). Indeed, there is little likelihood of conducting such experiments, for who would willingly undertake a long course of instruction on a keyboard not widely used in industry?

Surrogate measures of efficiency. In the absence of evidence from ideal research designs and their implementation, a surrogate for actual measures of speed has commonly been used; namely, key-to-key or finger-travel distances. Dvorak distances were regularly found to be greatly less than standard-keyboard distances (e.g., 37% less in Ober's 1993 study). However, the assumption (by Dvorak keyboard enthusiasts) that differences in finger travel equal or closely approximate differences in speed is based on a faulty model of skilled typing as a serial process, performed one keystroke at a time. Such a process applies only to novices, not to skilled typists. Gentner, Grudin, and Conway (1980) reported that highspeed filming of a 90-wpm typist revealed that "90% of the finger movements were initiated before the previous key was pressed" (p. 3) and that "in 51% of the cases where successive keys were typed by fingers on the same hand, the second keystroke was initiated while the first keystroke was still in progress" (p. 4). For skilled typists, a parallel, not a serial, model applies, consisting of a "coordinated structure that allows control of several fingers simultaneously" (Norman & Rumelhart, 1983, p. 54).

A simulation model of skilled typing. A motion picture of typing at 100+ words per minute (wpm) reminded its observers of "the movement of sea grass weaving in the waves, gracefully bending this way and that, all in motion at the same time" (Norman & Rumelhart, 1983, p. 47), and it stimulated the development by Rumelhart and Norman (1982) of a computer simulation model of skilled typing that produced an estimate of a 5.4% advantage in speed for the Dvorak over the standard keyboard.

The simulation model, however, includes several rough estimates in its bases (e.g., of finger lengths and of the extent to which a finger movement affects the positions of other fingers), and it does not take into account several characteristics of actual typing. For example, whereas there is a wide range of speeds for two-finger digraphs (ones typed by different fingers on the same hand, such as er mo), "the simulation model types them all at the same rate" (Gentner, Larochelle & Grudin, 1988, p. 526). Even so, as an indicator of the validity of the model, the actual times for six subjects to type the 66 most common digraphs yielded an overall correlation of about .86 with the times predicted by the model (Norman & Rumelhart, 1983, p. 62).

In any event, for various investigations based, at least in part, on measures of finger travel, Norman and Fisher (1982) reported that estimates of actual performance ranged from no significant differences to between five and ten percent superiority in speed for the Dvorak keyboard. Illustratively, Ober (1992) reported differences in studies conducted in the 1970s and 1980s of 2.6%, 5%, 6.2%, 11%.

Current status. The current state of affairs regarding the relative efficiencies of the standard and Dvorak keyboards may be summarized as follows: (1) key-to-key or finger-travel distances show very large advantages (i.e., lesser finger travel) for the Dvorak keyboard; (2) the various estimates of percentage differences in speed that were based on finger-travel measures, rather than actual typing, were a modest fraction of percentage differences in travel distances; (3) there are barriers to implementing ideal research designs applied to generating speed measures from full-keyboard use of the two keyboards.

Direct Measures of Speed.

As distinguished, from all earlier investigations, the research reported here provided direct (rather than inferred) measures of speed on both keyboards. In it, experienced standard-keyboard operators (with no knowledge of the Dvorak keyboard) typed digraphs on a standard keyboard and a matched set of their Dvorak-keyboard equivalents on a standard keyboard as if it were a Dvorak keyboard. The alphabet rows of the two keyboards are displayed in Figure 1.

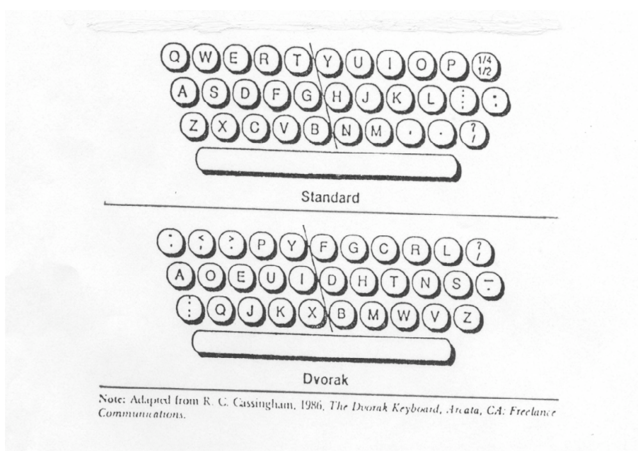

Figure 1. Alphabet rows of the standard and Dvorak typewriter keyboards.
(Adapted from R. C. Cassingham, 1986, *The Dvorak Keyboard, Arcata, CA: Freelance Communication*)

The research is theory- and hypothesis-free. The intent was to supply an unconfounded measure of the efficiencies (speeds) of the two keyboards, without hypothesizing the direction and size of whatever differences in speed might result.

As a prelude to a detailed account of procedures and their implementation, four features require explanation, as follows:

Digraphs. Digraphs, not prose, were used because units longer than two letters would have been unmanageable by standard-keyboard typists performing on an "as if" Dvorak keyboard. Also, the use of digraphs permitted adding to existing information on the speeds at which various types of digraphs can be typed and on whether speed varies with the frequency of occurrence of digraphs in printed English.

High speed. The instruction to subjects to type at high speed conflicts with the long-established orientation toward a rate of keystroking compatible with high accuracy. Had such an orientation been in effect, however, the overall difference in speed between the two keyboards would have been reduced, as would the differences in speed among the various types of digraphs.

Ten-second trials. Typing was confined to ten seconds per digraph. Preliminary trials, in which skilled typists repetitively types 2- and 3-letter words, at maximum speed, revealed that durations longer than ten seconds result in many errors beyond the 10-second point. That outcome is in accord with the classic research on the price paid for excessive repetition of small units of material, quoted by West (1983, p. 101).

Two trials at the digraphs. A second trial at typing the digraphs permitted assessing the reliability of scores under forced-speed conditions (test-retest reliability) and provided a more stable measure of speed at each digraph (the average of two trials) than one trial could supply.

METHOD

The procedures are described in turn for the subjects, the materials, the conditions of administration, and the scoring of the work. Because no hypotheses were under test (but with one exception), only descriptive statistics are reported (means, standard deviations, correlation coefficients).

Subjects. Eight experienced standard-keyboard typists (with no knowledge of the Dvorak keyboard) were used. Their skill levels-measured by a 3-minute straight-copy timing on ordinary prose under conventional conditions (a speed compatible with high accuracy)-ranged between 45 and 81 wpm (45, 53, 53, 60, 60, 71, 72, 81 wpm). That range encompasses the median speed of terminal high school trainees (44 wpm), through the 90th percentile speed of more highly trained persons (65.5 wpm), as reported by West (1983, p. 346), to beyond the 97th percentile speeds (74-78 wpm) of employees, as reported in the test manual accompanying the "Typing Test for Business" (Psychological Corp., 1968). The intent was to encompass a range of skill levels rather than to measure the differences in keyboard efficiencies of persons at each of several skill levels.

Materials. The 30 highest-frequency digraphs and their weights for relative frequency of occurrence in the language were included by Yardley in an article on solving cryptograms published in a popular magazine in 1931. They were reported by Dvorak, Merrick, Dealey, and Ford (1936, p. 377) and may have been a partial basis for the location of consonants on the Dvorak keyboard. Those digraphs were used here.

Each of the 30 digraphs was typed repetitively for ten seconds on the standard keyboard--and so were their Dvorak equivalents! For the digraph th, for example, the t and h on the Dvorak keyboard are in the k and j positions on the standard keyboard (see Figure 1). So typing kj on the standard keyboard is identical to typing th on the Dvorak keyboard. For another example, on the Dvorak keyboard the o and f of the digraph of are in the s and y positions on the standard keyboard; so typing sy on the standard keyboard is identical to typing of on the Dvorak keyboard. All told, then, the materials consisted of 30 digraphs typed on the standard keyboard and a matched set of 30 digraphs also typed on the standard keyboard as if it were a Dvorak keyboard. In effect, Yardley's 30 digraphs were typed on both keyboards. The 60 digraphs, accompanied by their weights for relative frequency of occurrence in the language, are displayed in Table 1.

Table 1
Standard and Dvorak Keyboard Digraphs and Their Weights*
(S = Standard, D = Dvorak, W = Weight)

	S	D	W		S	D	W		S	D	W
1.	th	kj	50	11.	at	ak	25	21.	st	;k	20
2.	er	do	50	12.	en	dl	25	22.	io	gs	18
3.	on	sl	39	13.	es	d;	25	23.	le	pd	18
4.	an	al	38	14.	of	sy	25	24.	is	g;	17
5.	re	od	36	15.	or	so	25	25.	ou	sf	17
6.	he	jd	33	16.	nt	1k	24	26.	ar	ao	16
7.	in	g1	31	17.	ea	da	22	27.	as	a;	16
8.	ed	dh	30	18.	ti	kg	22	28.	de	hd	16
9.	nd	lh	30	19.	to	ks	22	29.	rt	ok	16
10	ha	ja	26	20.	it	gk	20	30.	ve	.d	16

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**The digraphs (th . . . ve) are listed in Yardley's order of frequency, and the Dvorak equivalents permit typing them on the standard keyboard as if it were a Dvorak keyboard. The weights reflect the relative frequency of occurrence of the digraphs in English words.*

The standard-keyboard digraphs of Table 1 overlap substantially with those of other research on digraph frequencies. Of those 30 digraphs, 26 are among the most frequent 30, and 3 of the remaining 4 are among the next 30 of the digraphs tallied by Underwood and Schulz (1960). Of Yardley's 30, 22 are within the first 30, and 4 of the remaining 8 are within the next 30 of the 407 (non-zero) digraphs tallied by Mayzner and Tresselt (1965). Finally, Gentner's tallies from the computer tapes of the Kucera and Francis (1967) vocabulary of more than 50,000 different words revealed that Yardley's 30 digraphs accounted for 37% of all the occurrences of the 577 different alphabetic digraphs in that vocabulary (Personal communication, December 1993).

It may also be pointed out that among the digraphs of Table 1, 11 of the standard-keyboard digraphs are words, and the other 19 are familiar high-frequency components of words. Of the 30 Dvorak-keyboard digraphs, 2 are words and 14 are common components of words. Among the remaining 14 Dvorak digraphs, ; = s occurs in 4 digraphs and . (period) = v appears in 1 digraph. All the others among the "remaining 14" digraphs (except jd) occur in English words, however uncommon. Examples include (ao)rta, Ban(gk)ok, blac(kj)ack, chil(dh)ood, gir(lh)ood, tra(pd)oor, wit(hd)raw. However, typing uncommon letter sequences probably has no or no more than minuscule effects on digraph speed. For one thing, each digraph is typed in isolation, not embedded in a word; there is no context requiring attention during the typing. Mainly, under high-speed conditions, digraph typing is done mindlessly (without subvocalization of the letters making up the digraph)--analogous to executing an extended two-note trill on a piano keyboard.

Conditions of administration. The 10-second timings were administered to each subject individually, under instructions to type, without error correction, at one's highest speed short of getting tangled up and making frequent errors. For the pairs of digraphs of Table 1, administration was counterbalanced, alternating between the standard-keyboard digraph first and the Dvorak-keyboard digraph first (th kj do er on sl al an . . .), with spacing between digraphs during the timing (th th th . . .). Subjects used their preferred hardware: four of the eight used an IBM Selectric typewriter; the other four used a microcomputer keyboard. Similarly, the second trial with the 60 digraphs was administered immediately after the first trial or on the next day, at the option of the subject.

Lacking access to the high-technology hardware and software used by Rumelhart and Norman and their colleagues, as well as because the movement of the second hand on a stopwatch cannot be monitored with sufficient precision, I used a digital watch that blinks off the seconds. A 3-2-1 countdown (at 1-second intervals) triggered the beginning of the typing concurrent with (not after) the count of "1"; the rhythmic countdown enabled the subjects to accurately anticipate the "1." A sharply voiced "stop" ended the timing ten seconds later. Instant obedience to the "stop" command was evident; there were very many instances of timings ending with the first of the two letters in the digraph being typed. Between timings, a rest or pause of about ten seconds was typical.

To monitor the work, I sat beside, or looked over the shoulder of, the subject. Occasional infractions of the requirements evoked canceling the timing and starting anew. So did more than three or four misstrokes during the timing. Under a high-speed emphasis, repetition of short units of material, even for a work duration as short as ten seconds, often elicits at least a few errors.

Scoring procedure To express performance in the measure of words per minute, the number of keystrokes in 10 seconds (counted by a typing ruler calibrated in pica and elite spacing) was multiplied by 1.2. For example, 10 seconds is 1/6 of a minute; 50 keystrokes in 10 seconds = 300 strokes (60 "standard" 5-stroke words) in 1 minute, and 60/50 = 1.2.

Ten-second speeds, however, exceed 1-minute speeds; no typist can maintain for 60 seconds the speed of repetitive typing of digraphs for 10 seconds. As well, 10-second digraph speeds greatly exceed ordinary copying speeds. For example, the slowest (45-wpm) subject averaged 56 strokes per digraph (67 wpm); the fastest subject (81 wpm) averaged 113 strokes per digraph (136 wpm), with a maximum of 147 strokes (176 wpm) on one of the digraphs. Converting strokes in ten seconds to wpm is merely a reporting convenience. The 136wpm digraph typist is assuredly not a 136-wpm straight-copy typist.

RESULTS AND DISCUSSION

Results apply to the reliability of scores under forced-speed conditions, to the differences in speed between the two keyboards for digraphs unweighted and weighted for frequency, and to the speeds at which each of the various types of digraphs was typed.

Reliability

For the forced speeds on the first and second trials with the digraphs, the test-retest reliability coefficient was .88. Under ordinary conditions, examinees are urged to type at a rate that minimizes errors. Under such advice, reliability coefficients for speed in representative studies over a period of more than 40 years ranged from the low .80s to the high .90s, averaging (median) .87 (West, 1983, P. 136). So the reliability of the present data matches that of typical speed scores under conventional conditions.

Differences in Keyboard Efficiency

Table 2 displays the main outcomes of the research, expressed as strokes in 10 seconds and as words per minute (strokes x 1.2). For use in Table 2, the weights shown in Table 1 were scaled so as to have a mean of 1.0, resulting in outcomes more readily understandable than if the original (Table 1) weights had been used. The scaling does not affect the percentage differences in speed between the keyboards.

Table 2
Means for Digraph Speeds on the Dvorak and Standard Keyboards
(Standard deviations in parentheses)

Keyboard	Strokes in 10 Seconds		Words per Minute	
	Unweighted	Weighted	Unweighted	Weighted
Dvorak	70.53 (23.62)	70.75 (36.33)	84.64 (28.34)	84.90 (43.60)
Standard	67.80 (21.51)	68.29 (35.41)	81.36 (25.81)	81.95 (42.49)
Difference	2.73 (17.47)	2.47 (17.78)	3.28 (20.96)	2.96 (21.34)

*Words per minute = strokes x 1.2.

The outcomes shown in Table 2 will disappoint enthusiasts for the Dvorak keyboard. There was only a 4.0% superiority (2.73/67.80) for the Dvorak keyboard (unweighted) and a 3.6% superiority (2.47/68.29) for weighted digraphs. It may be mentioned in passing that a *t* test was applied to the differences between the correlated keyboard means. For unweighted digraphs, $t(7) = 3.419$ $p, < .02$; for weighted digraphs, $t(7) = 3.039$ $p, < .02$. Effect sizes for the data are very small: .127 for unweighted digraphs, .070 for weighted digraphs.

Should digraph frequency be taken into account? Dvorak et al. (1936, p. 214) faulted the standard keyboard, claiming that its key locations did not take high-frequency digraphs into account, whereas the Simplified keyboard "fits hand-stroking skills to the sequence patterns of English words" (p. 218). The data of Table 2 show, however, that weighting for frequency had only tiny advantages: .22 strokes (.26 wpm) for the Dvorak keyboard and .49 strokes (.59 wpm) for the standard keyboard. None of the standard-keyboard digraphs of the present research are rare, however; th is only about three times as frequent as ve. The present data, therefore, neither support nor refute Dvorak's contention about digraph frequencies.

Is 4.0% a definitive difference. A reservation applies to the modest (4.0%) superiority in speed of the Dvorak keyboard--a reservation based on the very different behaviors of slow and fast typists. Gentner (1988) found that digraphs were typed at about the same speed by slow students, but at significantly different speeds by experts. Among the eight subjects of the present research (copying speeds of 45-81 wpm), in relation to the 81-wpm speed of the fastest typist, speeds in the 45-60 wpm range are relatively slow. The standard deviation associated with the mean strokes per 10 seconds of the fastest typist (mean of 112.94, SD of 22.41) was about three times as large as the standard deviations of five of the other seven subjects. In other words, among the slower typists there was only modest variation in their digraph speeds, thereby narrowing the possible differences between the keyboards and accounting, in part, for the modesty of the 4.0% difference in speeds.

In contrast, for the fastest typist, there was a difference of 10.82 strokes (12.98 wpm) between the keyboard means, conferring a 10.1% advantage for the Dvorak keyboard. Furthermore, $r = .71$, $p < .05$, for the correlation between the straight-copy and digraph speeds of the eight subjects. Differences in the efficiencies of keyboards apparently vary with the skill level of the typist. A recommendation in that regard is made later in this article.

Digraphs Types and Speeds

What features of the digraphs listed in Table 1 appear to account for the outcomes of the present research? There are 1- finger (1F), 2-finger (2F), and 2-hand (2H) digraphs. (The examples that follow are merely illustrative, consist only of standard-keyboard digraphs for the sake of clear understanding, and are not confined to those of Table 1.) Some 1F digraphs are doubles (oo ee nn tt, etc.), of which there are none among the digraphs of Table 1.

Other 1F digraphs consist of two different letters (de, rt, lo, sw, etc.), of which there are none among the Dvorak-keyboard digraphs listed in Table 1. Some 2F digraphs use adjacent fingers (in er as ve, etc.); others use nonadjacent fingers (on at st ea ar, etc.). Finally, there are 2H digraphs (do if nd pr fl, etc.).

Among skilled typists, the digraphs described and illustrated above are in rank order for speed: 1F doubles are slowest; 2H digraphs are fastest because they permit maximum overlap in motions. With occasional exceptions (among the digraphs of Table 1, some 2F-nonadjacent digraphs were faster than some 2H digraphs), the rank order for speed of the 60 digraphs of the present research are in accord with the rank order stated above.

Specific to the present research, for the 1F digraphs, mean strokes per 10 seconds were 55.42 (66.50 wpm). For the other categories, strokes (wpm) were: 2F-adjacent 65.64(78.77), 2F-nonadjacent 68.51(82.21), 2H 71.49(85.79). As compared to 2Fadjacent digraphs, 2F-nonadjacent digraphs are faster because they permit greater freedom of movement and, therefore, more facile overlap. More broadly, and in recognition that consonant-vowel-consonant (CVC) is the basic structure of words in English (and most other languages), Dvorak located all the vowels on the left side of his keyboard and the most common consonants on the right side (see Figure 1). That arrangement permits very large numbers of leftright-left and right-left-right sequences for the hands. Such 2-hand sequences involve the maximum overlapping of finger motions that is the main contributor to speed. Because of the vowels-left, consonants-right layout, 2-hand digraphs will inevitably be more frequent on the Dvorak than on the standard keyboard.

The standard/Dvorak tallies for the number of digraphs of each type among the 60 digraphs of Table 1 are: 1F 3/0, 2F-adjacent 7/3, 2F-nonadjacent 6/5, 2H 14/22. The unequal between-keyboard frequencies for each type of digraph are the inevitable result of the different keyboard layouts. Equal between-keyboard digraph distributions are precluded by having the same digraphs (Yardley's 30) typed on both keyboards. For example, of is typed on the standard keyboard, and sy typed on the standard keyboard is the Dvorak keyboard's of. No IF digraphs, fewer 2F-adjacent digraphs, and mostly the large predominance of 2H digraphs account for the superiority, however modest, of the Dvorak keyboard in the present research. A sufficiently larger number of digraphs than those used here would inevitably include on each of the keyboards all five of the types of digraphs described and illustrated at the beginning of this section on "Digraph Types and Speeds." Necessarily, the Dvorak keyboard would have many more of the fast 2-hand digraphs and fewer of the slow 1-finger digraphs than the standard keyboard.

Other generalizations about digraph speeds antedate the present research and have explanatory value. In general, if not in all instances, the greater the spread between the fingers on a hand, the faster the speed (e.g., af > ad > as; pu is probably faster than pj). Also, moving in towards the thumb is faster than moving in the opposite direction (e.g., er is faster than re, af is faster than fa). Also pertinent, whatever the materials being typed, is the causal factor that distinguishes novices from skilled typists. Among novices, cognitive factors dominate (where is such and such a key? what finger do I use?). Among skilled typists, motoric factors prevail (Gentner, 1983). Because cognitive constraints are minimal, skilled operators can seize the opportunities to overlap finger movements. The limits for speed are governed by the skeletal and muscular characteristics of the hands and fingers and by the features of the apparatus. For example, electronic keyboards permit faster speeds than slower-acting manual typewriters. Response speeds at the piano exceed those at modern (electronic) typewriter keyboards, showing that such keyboards do not exhaust the response capacities of the fingers.

IMPLICATIONS FOR ADOPTION OF THE DVORAK KEYBOARD

Yamada (1980) and Ober (1992) have offered several reasons-despite widespread publicity in favor of the Dvorak keyboard--for the failure of the schools and industry to adopt the Dvorak keyboard many years ago. Computerization has perhaps created a climate more hospitable toward change, especially in the direction of increased productivity. Does current information about the relative merits of the Dvorak and standard keyboards support widespread adoption of the Dvorak keyboard? Concerning the adequacy of the presently available information on the efficiencies of the two keyboards, Cooper (1983, pp. 12-13) has asked whether component systems [e.g., digraphs] that can be rigorously studied in laboratory settings by "isolationists" are actual components of normal typing, studied by "naturalists." Is the 2.6% or 4.0% or 5.4% or 10% superiority of the Dvorak keyboard reported by isolationists likely to apply to normal typing in the classroom, on the job, and for personal uses? Nobody knows--because the necessary research, under appropriate experimental conditions, has never been carried out. Controlling for the hosts of variables that preclude attributing outcomes solely to the keyboard layouts is perhaps beyond accomplishment. Finding a sufficient number of subjects for the research is another major problem. In any event, the Dvorak keyboard may well be better than the outcomes of isolationist research suggest.

Despite the present absence of compelling "naturalist" evidence, but because computerization has created a vast market for increased productivity, possibilities for adoption of the Dvorak keyboard do exist. As Ober (1992, p. 178) has pointed out, modern technology readily transforms any microcomputer keyboard from a standard to a Dvorak layout (and vice versa). That capacity creates several inviting possibilities for trial of the Dvorak keyboard in normal settings. For personal use, anyone who wishes can try the Dvorak keyboard. Employers, however, have been unwilling to bear the costs (of as many as 100 hours) of retraining (distributed over several weeks). They have been immune to the argument that, because of increased productivity, retraining costs are quickly recouped, with continuous large savings thereafter because of increased productivity. More recently, a newspaper article illustrated and described radical new configurations of computer keyboards, most of which keep the standard (Qwerty) layout of keys (Feder, 1992). The article reports the assumption that "corporate customers will not be interested in a product that takes employees more than a few days to learn, particularly if they frequently use temporary help." The foregoing constraint does not totally preclude on-the-job adoption of the Dvorak keyboard, however. Consider that the overwhelming majority of applicants for jobs involving keyboard operation have acquired their skills via school training and that, in the classroom and on the job, modern microcomputer technology makes it easy to convert to a Dvorak layout of keys. Were the schools to install that technology, trainees intending employment at a keyboard would have the desired skills; they would not need to be retrained by employers who have installed the conversion technology. Current employees would continue at a standard keyboard; new job applicants would use the Dvorak keyboard. In time, as current employees retire and are replaced by newcomers, there could be wholesale use of the Dvorak keyboard on the job and in the schools.

There is a flea in the ointment, however. As Ober (1992, p. 176) has pointed out, although a few software tutoring programs for the Dvorak keyboard are available, teachers prefer print materials (currently nonexistent). What has been a problem for employers becomes, under the scenario outlined above, a problem for the schools and for the publishers of educational materials to deal with. Time, as usual, will tell.

CONCLUSIONS AND RECOMMENDATIONS

The modest 4.0% advantage for the Dvorak keyboard of the present research is within the range of outcomes of the earlier digraph research on the merits of the standard and Dvorak keyboards. That aside, the novel methodology of using a familiar keyboard to test the relative efficiency of an alternative keyboard has generic applicability to any such keyboard comparisons, whatever the configuration of the alternative keyboard. In place of surrogate measures of efficiency or of reliance on a computer model of skilled performance that is not as complete and precise as might be desired, the direct measure of speed provided by the procedures used here is easy to apply and permits differences in outcomes to be attributable entirely to keyboard layout. Whether present outcomes underestimate differences in performance of realistic tasks as between the Dvorak and standard keyboards remains to be seen.

A recommendation. The 4.0% difference in digraph speeds found across all eight subjects, but the 10.1% difference for the fastest typist in the present research, hints at a possibility. The relationship between the skill levels (straight-copy speeds) and the digraph speeds of the eight subjects ($r = .71$) strongly suggests that differences in keyboard efficiencies vary with the level of typing skill. It seems desirable to test that hypothesis. Is the difference in efficiency as between keyboard A and keyboard B of size X among 50-wpm typists, say, but of size Y among 80-wpm typists? In so doing, the typical skill level of employees (wpm speeds in the mid-50s) is the skill level of greatest interest. In any event, if high-technology apparatus can replace the use of a digital watch for timing 10-second trials, so much the better.

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