Analysis of Alternative Keyboards Using Learning Curves

Allison M. Anderson, North Carolina State University, Raleigh, North Carolina, **Gary A. Mirka,** Iowa State University, Ames, Iowa, and **Sharon M. B. Joines** and **David B. Kaber,** North Carolina State University, Raleigh, North Carolina

Objective: To quantify learning percentages for alternative keyboards (chord, contoured split, Dvorak, and split fixed angle) and understand how physical, cognitive, and perceptual demand affect learning. **Background:** Alternative keyboards have been shown to offer ergonomic benefits over the conventional, single-plane QWERTY keyboard design, but productivity-related challenges may hinder their widespread acceptance. **Method:** Sixteen participants repeatedly typed a standard text passage using each alternative keyboard. Completion times were collected and subsequent learning percentages were calculated. Participants were asked to subjectively rate the physical, cognitive, and perceptual demands of each keyboard, and these values were then related to the calculated learning percentages. **Results:** Learning percentage calculations revealed the percentage for the split fixed-angle keyboard (90.4%) to be significantly different ($p < .05$) from the learning percentages for the other three keyboards (chord, 77.3%; contour split, 76.9%; Dvorak, 79.1%). The average task completion time for the conventional QWERTY keyboard was 40 s, and the average times for the fifth trial on the chord, contoured split, Dvorak, and split fixed-angle keyboards were 346, 69, 181, and 42 s, respectively. **Conclusions:** Productivity decrements can be quickly regained for the split fixed-angle and contour split keyboard but will take considerably longer for Dvorak and chord keyboards. The split fixed-angle keyboard involved physical learning, whereas the others involved some combination of physical and cognitive learning, a result supported by the subjective responses. **Application:** Understanding the changes in task performance time that come with learning can provide additional information for a cost-benefit analysis when considering the implementation of ergonomic interventions.

INTRODUCTION

The basic, single-plane QWERTY keyboard has long been the conventional keyboard used in the office environment. Concerns related to the prevalence of work-related musculoskeletal disorders of the upper extremity in computer users (e.g., Gerr et al., 2002; Gerr, Monteilh, & Marcus, 2006) have prompted designers to develop alternative keyboard designs that (a) reduce ulnar deviations of the wrists (e.g., split keyboards), (b) reduce finger motion (e.g., contoured split keyboards and chord-style keyboards), and (c) make better use of the dominant fingers (second and third digits) by altering the position of the letters on the keyboard (e.g., Dvorak keyboard).

One impediment to the widespread acceptance of these alternative keyboards is the perception of a reduction in typing productivity over the short term, over the long term, and/or permanently. A number of studies have attempted to quantify this productivity impact and how, in the short term, it changes as a person becomes more proficient with the new keyboard (e.g., Chen et al., 1994; Fagarasanu, Kumar, & Narayan, 2005; Gerard, Jones, & Wang, 1994; Smith & Cronin, 1993; Swanson, Galinsky, Cole, Pan, & Sauter, 1997; Zecevic, Miller, & Harburn, 2000). Zecevic et al. (2000) evaluated the performance of 16 experienced computer users with a split fixed-angle keyboard and showed that after 10 hr of use, participants' typing speed was at about 90%

Address correspondence to Gary A. Mirka, Department of Industrial and Manufacturing Systems Engineering, Iowa State University, Ames, IA 50011-2164; mirka@iastate.edu. ***HUMAN FACTORS,*** Vol. 51, No. 1, February 2009, pp. 35-45. DOI: 10.1177/0018720808329844.

Figure 1. The four alternative keyboards used in this study: chord (top left), contoured split (top right), Dvorak (bottom left), split fixed angle (bottom right).

of their speed with the conventional QWERTY design. In a study of a contoured split keyboard (Figure 1, top right), Gerard et al. (1994) showed that 6 professional typists were able to type with 72% of baseline QWERTY speed after 115 min of use.

The split fixed-angle keyboard and contoured split keyboards described in the previous paragraph have different physical geometries than the conventional QWERTY keyboard but still maintain the QWERTY layout of the keys. Two other keyboards have been proposed that do not employ the QWERTY layout. The Dvorak keyboard uses a more purposeful layout of the letters of the alphabet, on which the right hand does 56% of the typing (versus 43% on the QWERTY keyboard). Furthermore, about 70% of typing is performed on the home row, thereby minimizing the movements of the fingers. Dvorak claimed that his keyboard layout could improve typing speed by 35% on typewriters (Dvorak, 1943). Subsequent authors have questioned these estimates (Alden, Daniels, & Kanarick, 1972; Norman & Fisher, 1982). The chord keyboard, likewise, does not use the QWERTY layout.

On a chord keyboard, each letter has a specific key combination (single key or multiple keys) that is simultaneously pressed, similar to chords in music, to produce a given character (or word). Productivity of the chord keyboard approach has been explored in several studies (e.g., Gopher & Raij, 1988; Kroemer, 1992; McMulkin & Kroemer, 1994). In a study of 10 participants from a university population, Kroemer (1992) showed that participants were able to memorize 59 chords for a two-handed ternary chord keyboard (eight keys, one for each finger) within about 3 hr. In a subsequent performance analysis, participants showed a significant increase in typing speed (from 36 to 70 characters per min [cpm]) after about 7 hr of typing with the chord system.

Gopher and Raij (1988) tested 15 participants with no typing experience and placed them into one of three groups: QWERTY, one-handed chord keyboard, or two-handed chord keyboard (the two-handed chord was two separate one-hand chord keyboards, each standing on its own). After 35 one-hr training sessions, chord users could type 160 cpm, whereas QWERTY users could type only about 105 cpm. With significant training, the chord keyboard appeared to yield higher productivity than the QWERTY keyboard for novices.

Although the aforementioned studies provide some data on change in productivity as a function of training time, none has used learning curve analysis to provide standardized measures for comparison across studies. Learning curve theory provides a structured, mathematical approach to predicting how task time decreases with repetition. It can be used to predict how long it will take for a person to reach a given level of performance on a task. As tasks become more complex, learning time increases. The standard equations used to find the learning percentage for a task (Wright, 1936) are

$$Y_x = KX^N, \text{ or} \quad (1)$$

$$N = \log (Y_x/K) / \log (X), \text{ and} \quad (2)$$

$$\text{Learning Percentage} = 100*2^N, \quad (3)$$

where Y_x = production time for Xth unit in sequence, K = time required for first unit, X = number of production units, and N = the slope of the line describing change in completion time (y) as a function of repetition number (x) in log-log space.

Accurate predictions of future productivity are important in industry, and therefore learning percentage values for many industrial tasks have been quantified in the literature (Konz & Johnson, 2000). Researchers have further explored these relationships and provided estimates for learning percentages based on the nature of the task being learned. Cognitive learning percentages have been shown to be approximately 70%, whereas more physical motor learning percentages are about 90%, and tasks involving both physical and cognitive learning are somewhere in between (Dar-El, Ayas, & Gilad, 1995). More dramatic changes in time to complete a task in the early trials of the task are represented by a lower learning percentage (steep descent in the learning curve), whereas more moderate changes in these times are represented by a higher learning percentage (shallow descent in the learning curve).

Interestingly, although the research noted earlier has quantified changes in productivity while typing on alternative keyboards, no studies have linked this learning to the physical, cognitive, and/or perceptual demands of these different keyboard designs. The specific objectives of this study are to quantify learning percentages for four alternative keyboards (split fixed angle, contour split, chord, and Dvorak) and understand how physical, cognitive, and perceptual demands affect these learning percentages.

METHODS

Participants

Twenty-five participants (14 male, 11 female) were recruited from the university population. Participants ranged in age from 18 to 30, with an average age of 24 years. All participants were right-handed with 20/20 or corrected-to-20/20 vision. Potential participants were excluded from study if they had current or chronic back, shoulder, neck, or wrist pain.

Participants were required to be able to type at least 25 wpm on the conventional QWERTY keyboard (Fagarasanu et al., 2005; Szeto & Ng, 2000). The average typing speed of the participants on the conventional QWERTY keyboard was 63 wpm (standard deviation 14.6; range 30 to 83), and all used a keyboard regularly. The participants provided written informed consent prior to participation.

Equipment

Participants were asked to key on five keyboards in this experiment (Figure 1): (a) conventional QWERTY keyboard, (b) split fixed-angle keyboard (Microsoft Natural, Microsoft Corporation, Redmond, WA), (c) contoured split keyboard (Kinesis Ergonomic Keyboard, Kinesis Corporation, Bothell, WA), (d) Dvorak keyboard layout, and (e) chord keyboard (BAT personal keyboard by Infogrip, Inc., Ventura, CA). The computer workstation was set up according to American National Standards Institute/Human Factors Society (ANSI/HFS) standards (Human Factors and Ergonomics Society,, 1988). The split fixed-angle keyboard had a slant angle of 12° (opening angle of 24°) and a tilt (gable angle) of 10°. The contour split keyboard had a split-rotational angle of 12°, lateral inclination of 20°, and 27 cm between keypads for each hand.

The typing trials were performed on a computer using the freeware typing program Stamina 2.0. Prior to the experimental trials, participants worked with the Stamina typing software package to become familiar with its operation. Stamina 2.0 forced the typist to type the passage correctly, thus prohibiting him/her from making a speed–accuracy trade-off by holding accuracy constant (at perfection) while completion time varied. The passage moved across the screen in a line as typing progressed, and no movement occurred if a wrong key was pressed. The trial passage contained 225 characters, including spaces, and contained all letters of the alphabet (according to common frequency-of-use data presented by Ridley, Dominguez, & Walker, 1999), two commas, three periods, and no numbers. After each trial, the experimenter recorded completion time (in seconds), error percentage, and typing speed (cpm).

Subjective assessment data were also collected. Participants were asked to rate each alternative keyboard in comparison to the conventional keyboard in terms of three workload demands, including physical demand, cognitive demand, and perceptual demand, by using visual analog scales (VAS). Participants' assessments of demands were motivated by the following questions:

- Cognitive demand: How much mental activity was required (e.g., remembering, thinking, deciding, or planning)?
- Physical demand: How much physical activity was required (e.g., finger coordination, awkward postures [shoulder, elbow, fingers], muscle force or tension, or awkward reaches with fingers)?
- Perceptual demand: How much perceptual activity was required (e.g., looking, searching, detecting, or recognizing)?

The survey was based on the form of the NASA Task Load Index (TLX) questionnaire (Hart & Staveland, 1988) and was similar to the adaptation used by Ma (2002). Each VAS used in the demand rating survey was 5 inches in length with *low* and *high* anchors as well as a midline drawn at 2.5 inches, identified on the VAS as the conventional QWERTY keyboard condition. Defining the scale midline in terms of the conventional QWERTY alternative allowed for the other keyboard designs to be rated above or below it in terms of workload for all three demand types. Any keyboard scoring above 2.5 inches on the VAS was rated higher in demand than the QWERTY keyboard, and any keyboard scoring lower than 2.5 inches was rated lower in demand than the conventional QWERTY keyboard.

Experimental Design

This study employed a repeated-measures experimental design with one independent variable (keyboard) with four levels: split fixed angle, contoured split, Dvorak, and chord. The dependent variables in this study were learning percentage and subjective assessment of cognitive demand, physical demand, and perceptual demand.

Experimental Protocol 1

Sixteen participants participated in a protocol to establish the learning percentages for the various keyboard alternatives. Before the typing trials, each participant was given 1 min to review the three-sentence passage. He or she was then asked to type the passage 10 times on a conventional QWERTY keyboard and to type as quickly as possible to record a baseline QWERTY typing speed. This provided further opportunity for the participant to become familiar with the passage. The participant was given 15 s rest between each typing trial.

Once the participant finished the 10 trials on the conventional QWERTY keyboard, he or she typed the same passage five times on each alternative keyboard (following a within-subjects experimental design with the order of keyboard presentation being completely randomized). The same passage was used in the training and in each trial to prevent any passage learning effects in the analysis. The participant was briefly instructed on how to use each keyboard and was given a "cheat sheet" showing the letters encoded by each key on both the Dvorak and the chord keyboard. After each of the five trials, the participant took a 15-s break. This "learn-by-doing" approach was taken to simulate the introduction of an ergonomics intervention into the workplace.

After each set of five trials with a specific keyboard, the participant completed the subjective assessment using the VAS and was then given a 3-min break. The complete experimental protocol lasted approximately 2 hr.

Experimental Protocol 2

Nine additional participants were asked to participate in another testing protocol that sought to validate the use of the "five-trial" protocol for establishing estimates of the learning percentages for the keyboards. In this protocol, each participant performed 10 trials on the QWERTY keyboard (as described earlier) and then performed the typing task 20 times on one of the alternative keyboards. After each trial, the participants were given a 15-s break with 1 additional min after each set of five trials on the alternative keyboard.

Three alternative keyboards were tested in this protocol (chord, Dvorak, and contour split) with each participant working with only one alternative keyboard (following a between-subjects experimental design). The split fixed-angle keyboard was not used in this protocol because Protocol 1 showed that participants could type within 5% of baseline QWERTY speed with only five trials. (Three participants used each alternative keyboard.) Experimental session time varied as a function of keyboard type, but all participants finished the protocol in less than 2 hr.

Data Processing and Statistical Analysis

Learning percentage provides information about the nature of the relationship between change in task performance time and trial number. The standard calculation for learning percentage was used (Equations 2 and 3) for the data from Protocol 1, where the time for Trial 1 (K) and time for Trial 5 (Y_5) were used to create the learning percentage (using $X = 5$). A similar calculation was performed for the data from Protocol 2. (Time for Trial 1 [K] and time for Trial 20 [Y_{20}] were used to create the learning percentage [using $X = 20$].)

Participants' subjective ratings of the keyboard demands were measured from the midlines of the VASes and given a score ranging from –40 to 40 (each point representing one 16th of an inch from a scale midline). Survey scores were then normalized to reduce interparticipant variability (Ma, 2002) using the following technique.

For a given participant and a given demand type, the largest rating deviation from the midline of the VAS was given a score of 1 (*high*) or –1 (*low*), depending on the direction of deviation. For example, if a participant rating of physical demand for the split fixed-angle keyboard was 1.5 inches away from the midline of the scale in the negative direction, this would correspond to a score of –24. Let us also say that the physical demand rating with the largest deviation from the scale midline for the same participant occurred with the chord keyboard, yielding a score of 32. Therefore, the normalized physical demand score for the split fixed-angle keyboard for the participant would be –0.75 (–24/32), and the physical demand score for the chord keyboard would be 1.0 (32/32).

A repeated-measures analysis of variance (ANOVA) was used to evaluate the effect of keyboard on learning percentage and on subjective levels of cognitive, physical, and perceptual demand. All the analyses were performed with SAS 9.0 (Cary, NC). Prior to conducting the ANOVA, we tested the assumptions of the ANOVA technique and confirmed them using the graphical approach described in Montgomery (2004). A p value of less than .05 was the standard for significance.

A Tukey-Kramer post hoc analysis was performed to further evaluate any significant effects. To assess the data from Protocol 2, we performed simple t tests to evaluate the differences between the learning percentages found after 5 trials with the learning percentages after 20 trials.

RESULTS

Learning Percentage

The results of the ANOVA procedure showed a significant effect of keyboard on learning percentage, $F = 23.25$, $p < .001$ (Figure 2). The learning percentage for the split fixed-angle keyboard was 90.4% and was significantly different from the learning percentages for the other three keyboards, all of which were less than 80% (chord, 77.3%; contour split, 76.9%; Dvorak, 79.1%). Figures 3 and 4 show how performance changed across the five trials of the experiment (Figure 4 shows response as normalized to Trial 1 for each keyboard).

Figure 3 shows that the initial and subsequent trials for the two keyboards that were not the QWERTY key layout (Dvorak and chord) were much slower than the other two alternative keyboards with the QWERTY layout across the five trials. After five trials, speed on the Dvorak layout was 4 times slower, and speed on the chord keyboard was 8 times slower than speed on the split fixed-angle keyboard (Figure 3). This figure also shows that the average time for the QWERTY trials was 40.2 s, and the average time for the fifth trial on the split fixed-angle keyboard was 42.4 s (only 5% slower than QWERTY). The most significant drop in time

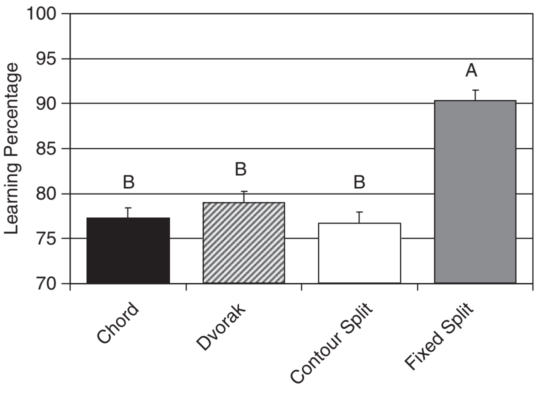

Figure 2. Learning percentage by keyboard type (standard error bars are shown). Columns with the same letter were not significantly different.

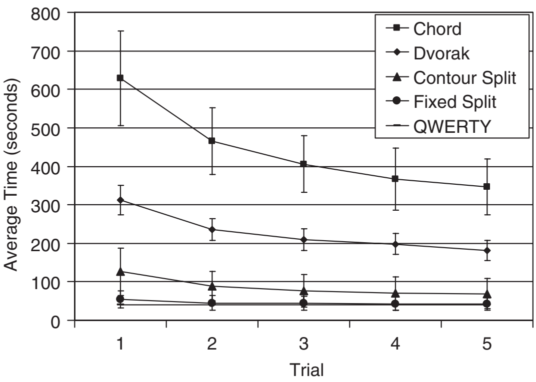

Figure 3. Time to complete the typing trials (+/– one standard deviation shown).

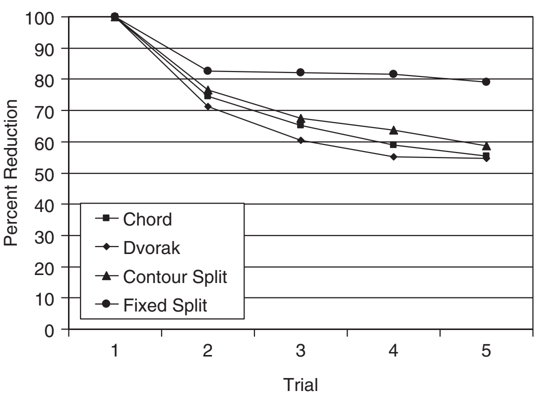

Figure 4. Normalized time to complete the typing trials.

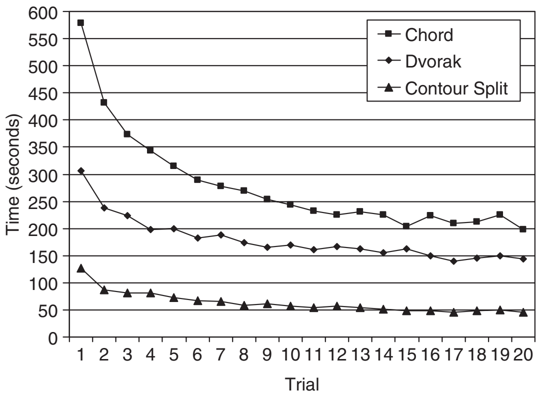

Figure 5. Time to complete the typing trials (20 repetition protocol only).

TABLE 1: Comparison of the Learning Percentages Calculated With 5 and 20 Trials of Data

	Learning %				
	5 trials		20 Trials		
Keyboard Type	*M*	*SD*	*M*	*SD*	*p* Value
Chord	77	7.5	78	3.7	0.43
Contour split	79	7.6	79	5.3	0.50
Dvorak	86	4.8	86	1.3	0.46

for Trials 1 to 2 was for the Dvorak keyboard (almost 30%).

Data collected during Protocol 2 showed no significant differences in the estimates of learning percentages calculated after 5 trials and 20 trials for each keyboard (Table 1 and Figure 5). For each alternative keyboard trial, there was less than 2% difference in the mean learning percentage for 5 trials and 20 trials. Additionally, after 20 trials on the contoured split keyboard (45 s per trial), participants were able to type within 11% of baseline QWERTY speed (40.2 s per trial).

Subjective Assessment of Demands

We found significant correlations between each demand type and learning percentage (Table 2). The negative correlation coefficient shows that a higher demand rating relates to a lower learning percentage. Therefore, more demanding tasks (whether the challenge is

TABLE 2: Correlations Between Learning Rate and Demand Type

Demand Type	Correlation Coefficient	*p* Value
Cognitive demand	–0.43	<.0001
Physical demand	–0.33	.0073
Percepyual demand	–0.29	.0209

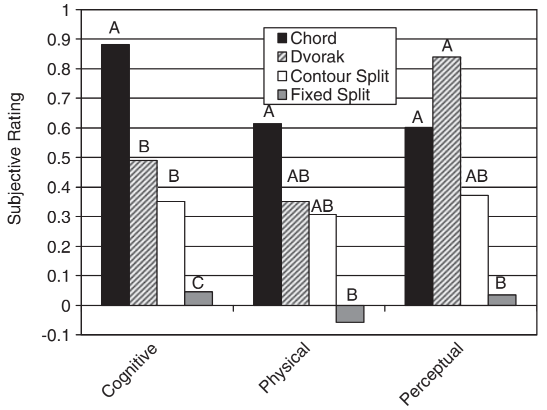

Figure 6. Subjective assessment of the physical, cognitive, and perceptual demands as a function of keyboard type. Columns with the same letter were not significantly different.

cognitive, physical, or perceptual) correspond to slower learning. For all three demand categories (cognitive, physical, and perceptual), there were statistically significant effects of keyboard (cognitive, $F = 18.98$, $p < .0001$; physical, $F = 3.90$, $p < .013$; and perceptual, $F = 10.38$, $p < .0001$; see Figure 6). The split fixed-angle keyboard was rated to be almost the same as the QWERTY in every category (with the QWERTY condition having a score of 0), but participants rated it slightly less physically demanding than the QWERTY. These scores also show that most participants felt the chord keyboard was the most cognitively and physically demanding, whereas the Dvorak keyboard was the most perceptually demanding.

DISCUSSION

One of the challenges that ergonomists often face when introducing ergonomics interventions in the workplace is the negative impact an intervention may have on the immediate and short-term productivity of the worker. This is not always the case, but when an operator has already reached some level of automaticity in a work task, changes in work methods or tools may require significant relearning of the task. This relearning may come in the form of the need to develop new motor control patterns for task execution or may require changes in higher-level cognitive processing. Under these conditions it would be expected that the time to do this task will increase in the short term, but it is also important to recognize that these productivity decrements are likely to be only transient and that productivity will increase, possibly exceeding that seen with the old methods. Learning curve theory provides a sound foundation on which one can build models that are capable of describing this profile of future productivity levels.

Alternative keyboards provide an interesting case study in the utility of this technique. The literature is positive in its assessment of the effects of many alternative keyboard designs on the reduction of exposure to recognized risk factors for upper-extremity musculoskeletal disorders (e.g., Baker & Cidboy, 2006; Hedge, Morimoto, & McCrobie, 1999; Honan, Serina, Tal, & Rempel, 1995; Marklin & Simoneau, 2001, 2004; Marklin, Simoneau, & Monroe, 1999; Rempel, Barr, Brafman, & Young, 2007; Simoneau, Marklin, & Berman, 2003; M. J. Smith et al., 1998; Strasser, Fleischer, & Keller, 2004; Tittiranonda, Rempel, Armstrong, & Burastero, 1999). It has also been demonstrated that there is an immediate negative effect on productivity for these alternative keyboards (e.g., note early trials in Figures 3 and 5) but that this negative effect is reduced and often completely eliminated with repetition of use. Models that are able to predict the productivity profile with continued use of these alternative keyboards provide valuable information for decision makers.

The learning percentages found in the present study of alternative keyboards reflect a range of learning percentages that are consistent with those that have been previously attributed to motor learning and cognitive learning (Dar-El et al., 1995). The data collected during the split fixed-angle keyboard trials generated a learning percentage of 90%, which is consistent with the "pure motor" description of this previously developed classification system. The learning percentages for the other three alternative keyboards were in the 75% to 80% range, which is described as a mixture of motor and cognitive learning with "more cognitive than motor" learning (Dar-El et al., 1995).

The high learning percentage (and the low initial completion time) on the split fixed-angle keyboard indicated less learning time and little lost productivity. In this design, the keys on the keyboard are in essentially the same location relative to the resting position of the fingers compared with the single-plane QWERTY design; only the angle of the forearms relative to the torso is modified. This causes only a minor change in the interaction between the operator and the keyboard. Participants quickly regained typing speed on the split fixed-angle keyboard in this study, showing the ability to type within 5% of the baseline conventional QWERTY speed with only five trials on the split fixed-angle keyboard. In general, the trials on the split fixed-angle keyboard were 1 min or less, so it took participants only 5 min of typing to regain baseline typing speed for this experimental task. This is much faster than previously reported studies.

Some studies reported that typing speed on the split fixed-angle keyboard was within 10% of standard after 8 hr of training (Fagarasanu et al., 2005) and 11% after 10 hr of training (Zecevic et al., 2000). There are some methodological differences between the current and previous studies that may account for these differences (e.g., duration of the typing trials, pool of participants, nature of the typing task). The results of this study illustrate that a split fixed-angle keyboard should be a relatively easy ergonomic intervention to introduce into the workplace, involving little learning time for skilled typists.

As with the split fixed-angle keyboard, the contoured split keyboard was assumed to be a more physical intervention, and the expectation was that the learning percentage would be approximately 90%. In this keyboard design, the contoured nature of the right- and left-hand keypads alters the required travel distance of the fingers from that required with the single-plane QWERTY, meaning that a slight modification of the motor control program is needed for a typist to find certain keys on the keyboard. In the current study, this change in required travel distance tended to generate errors in the keys that were depressed, thereby slowing the operator more than in the split fixed-angle design. Based on Dar-El et al.'s (1995) research, the learning percentage of 77% indicates a considerable cognitive contribution, possibly stemming from the need to remember how to move the fingers along the contoured surface to hit the appropriate key. This contention is also supported by the subjective responses provided by the participants, which revealed a significantly greater cognitive demand than the split fixed-angle keyboard.

Although the learning percentage of the contour split keyboard was the lowest of all four keyboards, the average typing speed on this keyboard at baseline was second to that of the split fixed-angle keyboard. Participants were able to type within 10% of baseline productivity (44.0 s to 40.2 s) after 20 trials or about 30 min of typing with the contour split keyboard. This result is consistent with pilot results presented by Treaster and Marras (2000), who found that participants were able to type at 86% productivity within an hour of using the contour split keyboard.

The learning associated with the Dvorak keyboard was hypothesized to be more cognitive in nature (primarily demands on memory), and the results of this study support this hypothesis with a learning percentage of 79%. Because the shape of the Dvorak keyboard tested in this experiment was the same as that of the QWERTY keyboard, participants often reverted to using the QWERTY key layout and had to concentrate to overcome the effects of negative skill transfer and remember the new layout. One interesting result with regard to the Dvorak layout is that although positioning of the keys on the keyboard is identical to that on the QWERTY, it was subjectively rated high in physical demand. This might have been because of participants' lack of proficiency with this particular key layout, which dictated different hand postures when typing familiar words and required different patterns of finger coordination.

The Dvorak design also produced high perceptual demand ratings. This was not surprising, as the new key layout forced participants to use a "hunt-and-peck" typing style (because they had not yet memorized the location of the individual keys). In general, participants were constantly looking, searching, and struggling to find the physical location of keys. Dvorak claimed that once participants were proficient with his keyboard, they typed 35% faster (Dvorak, 1943). However, other studies suggested that novice typists were, at most, 5% faster with the Dvorak keyboard, and it would not be worthwhile for expert typists to learn the new layout (Norman & Fisher, 1982). The cognitive, physical, and perceptual demand evaluation as part of this study revealed participant difficulty in use of the Dvorak keyboard for skilled typists, and these demands may be related to limited improvements in typing speed over the QWERTY design.

The chord keyboard was also hypothesized to involve considerable cognitive demand while also posing physical demand when participants tried to coordinate multiple fingers for typing a single letter. The results of this study support both of these hypotheses. The 77% learning percentage for the chord keyboard indicates combined cognitive and physical learning for this device, a result that was supported by the subjective assessment of demand. The chord keyboard was rated as the most cognitively (0.88) and physically (0.61) challenging of all four keyboards. Although trials on the chord keyboard were still much slower than those on the QWERTY keyboard after 20 trials (195 s vs. 40 s), other studies have reported more positive productivity results with longer training periods (Beddoes & Hu, 1994; Gopher & Raij, 1988; Kroemer, 1992). In addition, with only seven keys, the chord keyboard's number and location of keys are very different from those of the conventional QWERTY keyboard, which thereby limits the potential for negative skill transfer effects among proficient typists. Although training time was longest for this keyboard, it should also be noted that the one-hand design does accommodate a wider range of users (persons with only one hand available to type).

Being able to predict how productivity levels will change as a worker grows accustomed to a modified work task is part of the larger cost-benefit analysis that an ergonomist may need to perform to see an intervention implemented. The current study provides information with regard to the relearning costs associated with the implementation of an ergonomic intervention, particularly during this "familiarization" phase in which the time to complete a task may be 4 to 5 times (or more) higher relative to the productivity levels of the old method. In this larger cost-benefit analysis, this initial cost must be considered relative to the benefits of the intervention, such as the steady-state level of productivity, the reduction in costs arising from reduced injury risk, and improved quality. Ultimately, it is up to the decision maker to weigh the costs versus the benefits, but without a clear understanding of the expected changes in productivity over time that are attributed to learning, such an analysis cannot be complete.

Performing an experiment to build a predictive learning model requires time and money. It is not our intention with this research to encourage someone who is considering an ergonomic intervention to conduct such a formal study. Instead, our intention is to provide the research community with empirical data illustrating the utility of learning rate in the evaluation of an ergonomic intervention. This study has demonstrated a relatively efficient method for providing productivity profile estimates by utilizing a small number of participants on a relatively small number of experimental trials. Furthermore, in this research we have shown that understanding the nature of the intervention (relative levels of cognitive and physical learning) is an important dimension to consider when forecasting future productivity levels. Previous studies had indicted a relationship between these types of learning and learning percentages, and the results of the current study support these relationships in an ergonomic intervention scenario. It is our hope that if the impact of an ergonomic intervention on productivity is predictable, industry can make a more informed decision when performing a cost-benefit analysis of the intervention prior to its introduction into the workplace.

There are several limitations to the current work that should be considered. One limitation is that we designed this experiment to focus on the familiarization stage of an ergonomic intervention without providing any kind of structured training with the intervention. It has been our experience that introduction without any formal training is the way that many interventions are implemented; however, focused training with the intervention could provide an even more rapid reduction in cycle times and improved cost justification for the intervention.

Second, the generalizabilty of the results of this study is limited because of the controlled nature of the laboratory study. We chose to employ a single standard passage for the typing trials as a variance reduction technique that would allow for a more direct interpretation of the results relative to learning the use of the alternative keyboard. Future work could consider this effect and evaluate the effect of a dynamic text on these estimates of the learning percentages. Also, only proficient typists (those who type at least 25 wpm) were tested in this experiment. Neither hunt-and-peck typists nor elite touch typists were specifically recruited for this study, and therefore the effects of negative transfer (touch typists) or lack of initial skill (hunt-and-peck typists) were not considered, and the learning percentages could be affected by these characteristics.

CONCLUSIONS

Learning percentages associated with alternative keyboards were explored in this study. The learning percentage for the split fixed-angle keyboard was 90.4% and was significantly different from the learning percentages for the other three keyboards, which all were less than 80% (chord, 77.3%; contour split, 76.9%; Dvorak, 79.1%). Subjective assessment of the physical, cognitive, and perceptual demands of each keyboard provided critical insight into the nature of the learning process. The chord keyboard was rated most demanding in both the physical and cognitive dimensions, and the Dvorak keyboard was rated highest in the perceptual demand category. These results provide quantitative and predictive information about future productivity levels that can be achieved using alternative keyboards.

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Allison Anderson is an ergonomist at the Ergonomics Center of North Carolina. She received her master's degree in industrial engineering from North Carolina State University in 2007.

Gary Mirka is a professor and chair of the Department of Industrial and Manufacturing Systems Engineering at Iowa State University. He received his Ph.D. in industrial and systems engineering from The Ohio State University in 1992.

Sharon Joines is an assistant professor in the Department of Industrial Design at North Carolina State University. She received her Ph.D. in industrial engineering from North Carolina State University in 2002.

Dave Kaber is a professor in the Edward P. Fitts Department of Industrial and Systems Engineering at North Carolina State University. He received his Ph.D. in industrial engineering from Texas Tech University in 1996.

Date received: August 3, 2007
Date accepted: October 31, 2008