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Analysis of Alternative Keyboards Using Learning Curves

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ABSTRACT

Objective: 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 ($p<0.05$) 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 seconds, and the average times for the 5th trial on the chord, contoured split, Dvorak and split fixed-angle keyboards were 346, 69, 181 and 42 seconds, 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 while 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.

KEY WORDS: alternative keyboards, learning curve theory, ergonomic interventions, DVORAK, chord keyboards, split keyboards, musculoskeletal disorders

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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 1) reduce ulnar deviations of the wrists (e.g. split keyboards), 2) reduce finger motion (e.g. contoured split keyboards and chord style keyboards), and 3) make better use of the dominant fingers (2nd and 3rd 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, the long term, and/or permanently. A number of studies that 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. Smith & Cronin, 1993; Chen, Burastero, Tittiranonda, Hollerbach, Shih, & Denhoy, 1994; Gerard, Jones, & Wang, 1994; Swanson, Galinsky, Cole, Pan, & Sauter, 1997; Zecevic, Miller, & Harburn, 2000; Fagarasanu, Kumar, & Narayan, 2005). Zecevic et al. (2000) evaluated the performance of 16 experienced computer users with a split fixed-angle keyboard and showed that after 10 hours of use, participant's typing speed was at about 90% 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 six professional typists were able to type with 72% of baseline QWERTY speed after 115 minutes 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 with 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) was able to show that participants were able to memorize 59 chords for a two-handed ternary chord keyboard (eight keys, one for each finger) within about 3 hours. In a subsequent performance analysis, participants showed a significant increase in typing speed (from 36 to 70 characters per minute (cpm)) after about 7 hours 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 could stand on their own). After 35 one-hour training sessions, chord users could type 160 cpm while QWERTY users could only type about 105 cpm. With significant training, the chord keyboard appeared to yield higher productivity than the QWERTY keyboard for novices.

While the above studies provide some data on change in productivity as a function of training time, none have 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 is (Wright, 1936):

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

$$N = \log (Y_x/K) / \log (X) \quad (2)$$

and

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

Where:

Y_x: production time for Xth unit in sequence
K: time required for first unit
X: number of production units
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 and 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 around 70%, while 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), while more moderate changes in these times are represented by a higher learning percentage (shallow descent in the learning curve.) Interestingly, while the research noted above 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 18-30 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 words per minute 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 words/minute (standard deviation 14.6; range 30-83) 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): 1) conventional QWERTY keyboard, 2) split fixed-angle keyboard (Microsoft Natural, Microsoft Corporation, Redmond, WA), 3) contoured split keyboard (Kinesis Ergonomic keyboard, Kinesis Corporation, Bothell, WA), 4) Dvorak keyboard layout, and 5) chord keyboard (BAT personal keyboard by Infogrip, Inc., Ventura, CA). The computer workstation was setup according to ANSI/HFS standards (ANSI/HFS, 1998). 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 20°, and had 27cm 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. The Stamina 2.0 software forced the typist to type the passage correctly, thus prohibiting subjects to make 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 (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 and planning)?
- Physical Demand: How much physical activity was required (e.g. finger coordination, awkward postures (shoulder, elbow, fingers), muscle force/tension, or awkward reaches with fingers)?
- Perceptual Demand: How much perceptual activity was required (e.g. looking, searching, detecting, 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 terms of workload for all three demand types. Any keyboard scoring above 2.5” on the VASs was rated “higher” in demand than the QWERTY keyboard and any keyboard scoring lower than 2.5” 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, the participant was given one minute to review the three-sentence passage. The participant was then asked to type the passage ten times on a conventional QWERTY keyboard and to type as quickly as possible in order 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 seconds rest between each typing trial.

Once the participant finished the 10 trials on the conventional QWERTY keyboard, they 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 chord keyboards. After each of the five trials, the participant took a 15 second 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-minute break. The complete experimental protocol lasted approximately 2 hours.

Experimental Protocol 2

Nine additional participants were asked to participate in another testing protocol that sought to validate the use of the ‘5-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 above) and then performed the typing task twenty times on one of the alternative keyboards. After each trial, the participants were given a 15-second break with one additional minute 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 only working with 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 hours.

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) was 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}) was used to create the learning percentage (using X=20)).

Participant subjective ratings of the keyboard demands were measured from the midlines of the VASs and given a score ranging from -40 to 40 (each point representing 1/16 inch from a scale midline). Survey scores were then normalized in order to reduce inter-participant variability (Ma, 2002) using the following technique. For a given subject 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" 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 (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 of the analyses were performed with SAS 9.0 (Cary, NC). Prior to conducting the ANOVA, the assumptions of the ANOVA technique were tested and confirmed using the graphical approach described in Montgomery (2004). A p-value of less than 0.05 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, simple *t*-tests were performed to evaluate the differences between the learning percentages found after five 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, which all 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 over the five trials. After five trials, speed on the Dvorak layout was four times slower and speed on the chord keyboard was eight 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 seconds, and the average time for the 5th trial on the split fixed-angle keyboard was 42.4 seconds (only 5% slower than QWERTY. The most significant drop in time 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 five 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 five trials and 20 trials. Additionally, after 20 trials on the contoured split keyboard (45 seconds per trial), subjects were able to type within 11% of baseline QWERTY speed (40.2 seconds per trial).

Subjective Assessment of Demands

There were significant correlations between each demand type and learning precentage (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 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: $F=18.98$, $p<0.0001$, physical: $F=3.90$, $p<0.013$, and perceptual: $F=10.38$, $p<0.0001$) (Figure 6). The split fixed-angle keyboard was rated to be almost the same as the QWERTY in every category (with the QWERTY condition being 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 while the Dvorak keyboard was the most perceptually demanding.

DISCUSSION

One of the challenges that ergonomists often face when introducing ergonomic 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. It would be expected under these conditions 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 we 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 quite positive in its assessment of the effects many alternative keyboard designs have on 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; 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 to decision-makers.

The learning percentages found in the present study of alternative keyboards reflect a range of learning percentages that are consistent with those which 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 75-80% 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 as compared to 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 minute or less, so it only took participants 5 minutes of typing to regain baseline typing speed for this experimental task. This is much faster than previously reported studies. Some studies reported typing speed on the split fixed-angle keyboard was within 10% of standard after 8 hours of training (Fagarasanu et al., 2005) and 11% after 10 hours 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 with little learning time for skilled typists.

Like 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 around 90%. In this keyboard design the contoured nature of the right and left hand keypads alter the required travel distance of the fingers from those required with the single plane QWERTY, requiring a slight modification of the motor control program required 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. (1995) research, the learning percentage of 77% indicates 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. While the learning percentage of the contour split keyboard was the lowest of all four keyboards, the average typing speed on the contour split keyboard at baseline was second to the split fixed-angle keyboard. Participants were able to type within 10% of baseline productivity (44.0 sec to 40.2 sec) after 20 trials or about 30 minutes 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 the QWERTY, participants often reverted back 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 while positioning of the keys on the keyboard is identical to the QWERTY, it was subjectively rated "high" in physical demand. This might have been due to participant lack of proficiency with this particular key layout dictating different hand postures in typing familiar words and requiring 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 (since 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 trying 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 a 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. While trials on the chord keyboard were still much slower than the QWERTY keyboard after 20 trials (195 seconds versus 40 seconds), other studies have reported more positive productivity results with longer training periods (Gopher & Raij, 1988; Beddoes & Hu, 1994; Kroemer, 1992). In addition, with only 7 keys, the number and location of the keys is very different from the conventional QWERTY keyboard, thereby limiting the potential for negative skill transfer effects for 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 only having 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 in order to have 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 wherein the time to complete a task may be 4-5x (or more) 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 due to reduced injury risk, and improved quality. Ultimately it is up to the decision-maker to weigh the costs vs. the benefits, but without a clear understanding of the expected changes in productivity over time due to learning, such an analysis is not 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 subjects on a relatively small number of experimental trials. Further, this research has 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 literature 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 of the limitations of the current research is that we have 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 are limited because of the controlled nature of the laboratory study. Using a single standard passage for the typing trials was employed 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 (type at least 25 words per minute) 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 while 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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Table 1: Comparison of the learning percentages calculated with five and 20 trials of data.

Learning %	**5 trials**		**20 trials**		**p-value**
	Mean	**St Dev**	**Mean**	**St Dev**	
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**

Table 2. Correlations between learning rate and demand type.

	Correlation Coefficient	p-value
Cognitive Demand	-0.43	<0.0001
Physical Demand	-0.33	0.0073
Perceptual Demand	-0.29	0.0209

FIGURES

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).

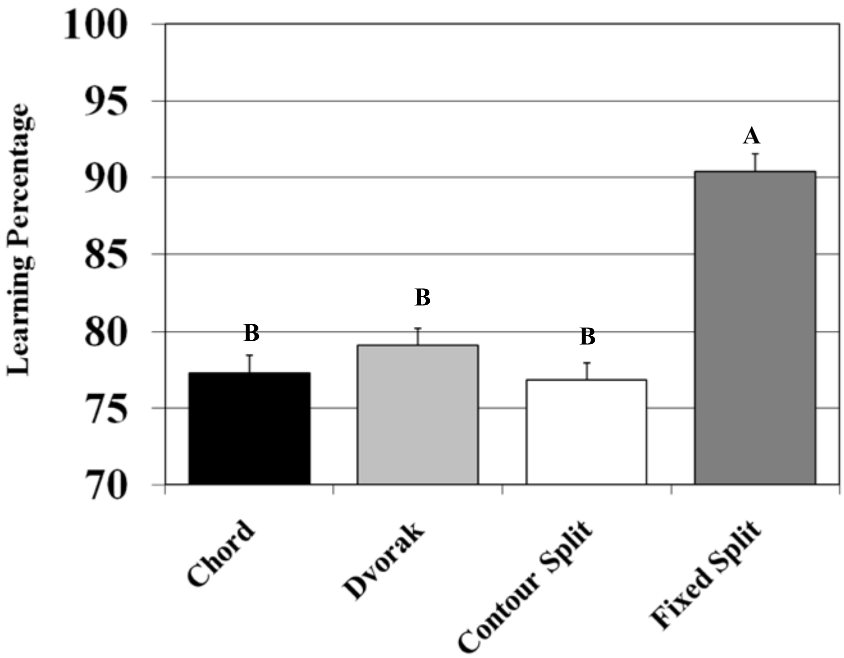

Figure 2: Learning percentage by keyboard type (standard error bars are shown). Columns with the same letter were not significantly different.

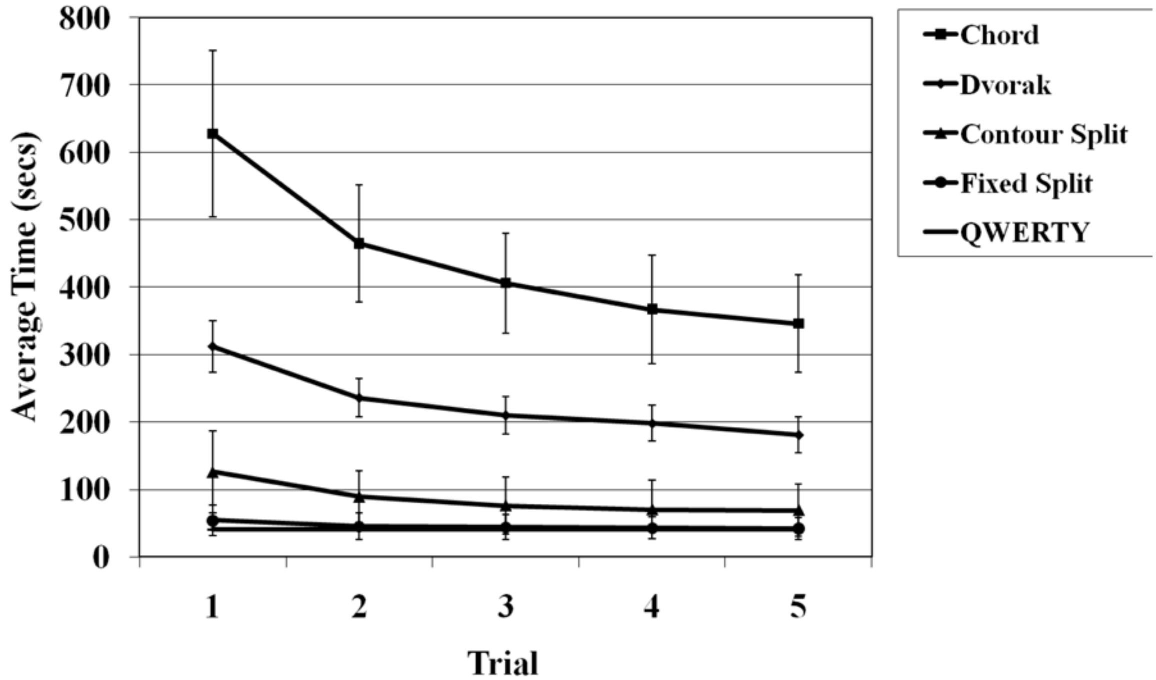

Figure 3: Time to complete the typing trials (+/- one standard deviation shown).

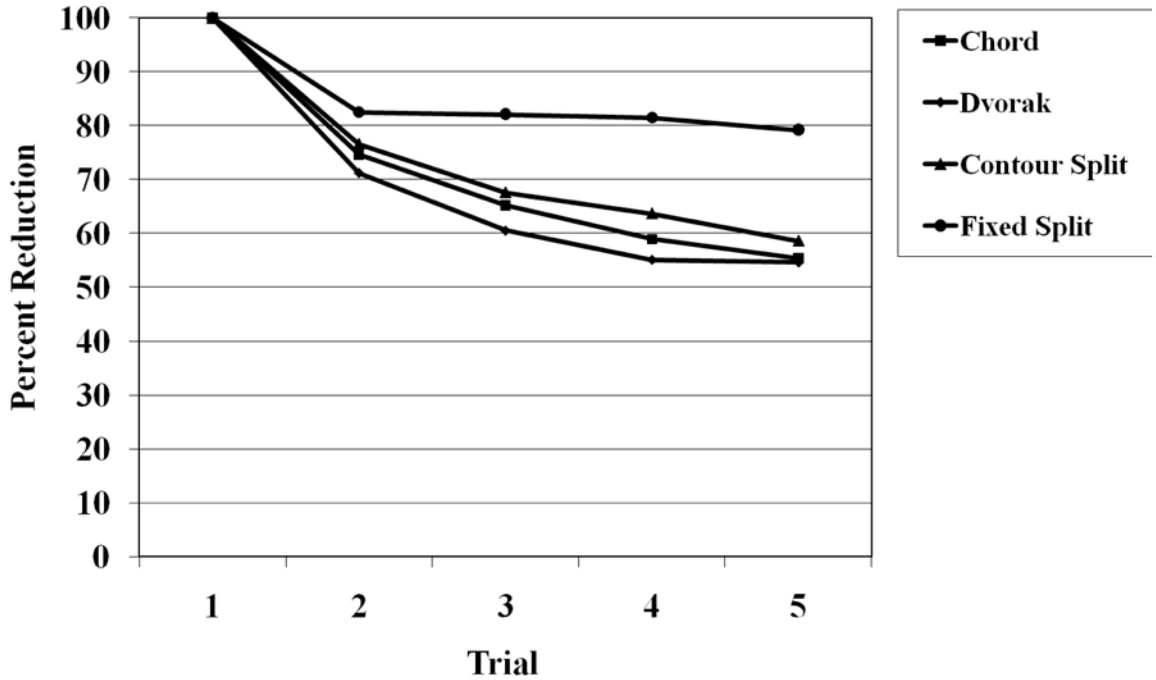

Figure 4: Normalized time to complete the typing trials.

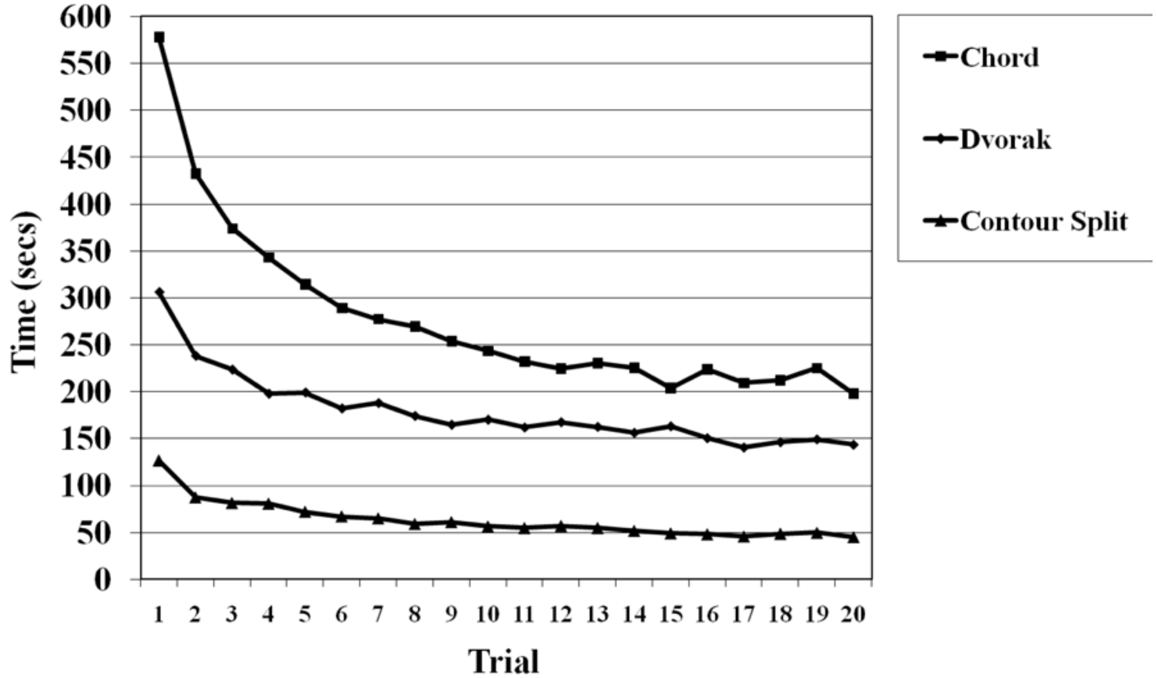

Figure 5: Time to complete the typing trials (20 repetition protocol only).

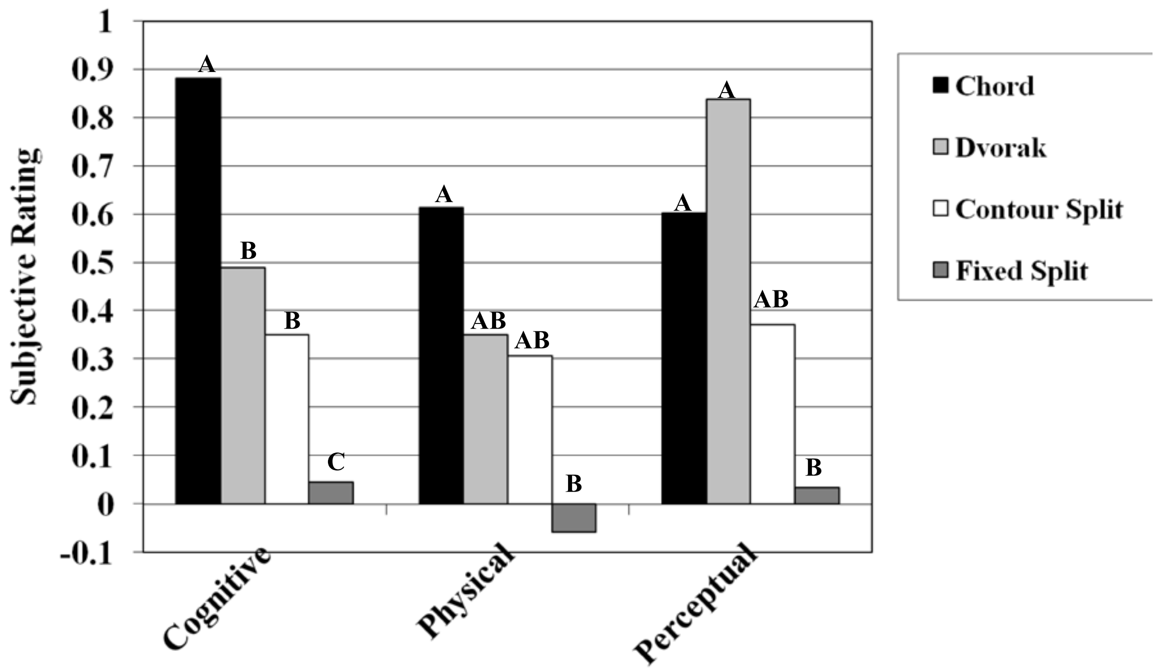

Figure 6: Subjective assessment of the physical, cognitive, and perceptual demands as a function of keyboard type. Columns with the same letter were not significantly different.