

A METHODOLOGY FOR DEVELOPING AN OPTIMAL AND
ERGONOMIC KEYBOARD LAYOUT FOR TOUCH TYPISTS AND ITS
APPLICATION TO TURKISH LANGUAGE

by

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ABSTRACT

A METHODOLOGY FOR DEVELOPING AN OPTIMAL AND ERGONOMIC KEYBOARD LAYOUT FOR TOUCH TYPISTS AND ITS APPLICATION TO TURKISH LANGUAGE

In this study, a new and novel method of developing both ergonomic and efficient keyboard layouts is introduced based on the touch typing principles. A multi objective mathematical model with two objectives is defined. One of the objectives is related with the speed of typing while the other is related with the distribution of typing load among the fingers according to their capabilities. The parameters of the model are desired target finger loads and digraph costs; and monograph and digraph frequencies of the letters in the specified language. The experimentally determined penalty parameters are universal that can be used in keyboard layout optimization of any language. An optimization technique, namely “non-dominated sorting genetic algorithm II (NSGA II)” with Pareto dominance approach, is used for the application of the model and developing an ergonomic and optimal keyboard layout for Turkish language. Based on the optimization results, three of the obtained 152 layouts that minimize both monograph and digraph penalties are selected as the candidates of the best keyboard layout for Turkish language. These selected layouts were compared with F and Q layouts through optimization results, Dvorak’s criteria and experimental validation studies considering tendon travel of fingers and typing speed. The results indicate that all three candidate layouts are better than the Q and F layouts according to the optimization results and Dvorak’s criteria. With respect to the experimental validation studies, total tendon travel of three candidate layouts were less than F and Q layouts. In addition, tendon travels of two candidate layouts were relatively evenly distributed across fingers compared to the Q and F layouts. For the typing speed criterion, candidate layouts were better than Q layout, but not significantly different than F layout. Based on the overall results, ‘E layout’ which is one of the candidate layouts is selected as the best layout for touch typing in Turkish language.

ÖZET

ON PARMAK KLAVYE KULLANICILARI İÇİN OPTİMAL VE ERGONOMİK BİR KLAVYE YERLEŞİMİ GELİŞTİRME METODOLOJİSİ VE TÜRKÇEYE UYGULANMASI

Bu çalışmada on parmak yazım prensipleri temel alınarak hem ergonomik hem de verimli klavye yerleşimleri oluşturmak için yeni ve özgün bir yöntem geliştirilmiştir. İki amacı olan çok amaçlı bir matematiksel model kurulmuştur. Amaçlardan birincisi yazım hızıyla, diğeri ise yüklerin parmaklara kapasiteleri gözetilerek dağıtılmasıyla alakalıdır. Modelin parametreleri istenen hedef parmak yükleri ve digraf maliyetleriyle birlikte ilgili dildeki harflerin monograf ve digraf sıklıklarıdır. Deneysel olarak belirlenen ceza parametreleri, herhangi bir dilin klavye yerleşimi optimizasyonunda kullanılabilecek evrensel parametrelerdir. Modelin Türk diline uygulanması ve Türk dili için optimal bir klavye yerleşiminin bulunabilmesi için Pareto baskınlık yaklaşımıyla “non-dominated sorting genetic algorithm II (NSGA II)” isimli optimizasyon tekniği kullanıldı. Optimizasyon sonuçlarından elde edilen 152 klavye yerleşiminden hem monograf hem de digraf cezalarını en aza indiren üç tanesi Türkçe’nin en iyi klavye yerleşimi olabilmesi için aday olarak seçildi. Bu seçilen yerleşimler, optimizasyon sonuçları, Dvorak’ın ölçütleri ve deneysel geçerlilik çalışmaları ile elde edilen tendon hareketi miktarı ve yazım hızı ölçütleri dikkate alınarak F ve Q yerleşimleriyle karşılaştırıldılar. Sonuçlar, tüm üç aday klavye yerleşiminin optimizasyon sonuçları ve Dvorak’ın ölçütlerine göre F ve Q yerleşiminden daha iyi olduğunu ortaya koydu. Tendon hareketi miktarı ölçütüne göre ise, her bir aday klavye yerleşiminin toplam tendon hareketi miktarı F ve Q yerleşimlerinkinden daha azdı. Ayrıca, iki aday yerleşimde tendon hareketlerinin parmaklar arasında dağılımı F ve Q yerleşimlerine göre daha düzenliydi. Yazım hızı kriterine göreyse, aday yerleşimler Q yerleşiminden daha iyiydi, ancak F klavye ile aralarında istatistiksel anlamda önemli bir fark yoktu. Sonuçların hepsi gözden geçirildiğinde, aday yerleşimlerden biri olan “E klavye yerleşimi” Türkçe on parmak yazım için en iyi yerleşim olarak seçildi.

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1. INTRODUCTION

In today's technologically developed world, the keyboard still is the main device for text entry in computers. However, due to the deficiencies in existing and commonly used keyboard layouts the text entry jobs induce health, comfort and performance problems. Hence, it is important to have a healthy and comfortable keyboard layout which also promotes fast text entry.

An examination of the history of the English keyboard layout indicates that the standard layout (QWERTY) is not optimized for efficient typing, but is actually quite arbitrary (Noyes, 1998). It was designed over a century ago and was even optimized to slow down typists to prevent the keys getting stuck in mechanical keyboards. These counter-optimized keyboards were justified for some decades during which mechanical problems remained in typewriters. However, it is not the case now.

Until now, several proposals for a keyboard arrangement optimizing a criterion such as typing speed or rapid learning of the typing system were made in different languages especially in English (Eggers *et al.*, 2003). Furthermore, some papers (e.g., Pollatschek *et al.*, 1975) investigated ergonomic criteria other than just typing speed, but did not insisted on either a realistic modeling or an optimization method that would have addressed the problem well. Eggers *et al.* (2003) used ergonomic criteria again in their novel mathematical model and used optimization procedure for solving this model. However, the ergonomic criteria that they used were formed by the subjective judgments of two ergonomists without making experiments. Yin and Su (2011) used the same ergonomic criteria values as the study of Eggers *et al.* (2003), however simplified their model and used a different optimization technique. Thus, until now no study has been done to the optimization of a realistic keyboard arrangement taking account of ergonomics and efficiency criteria with objective model parameters that are obtained through experiments.

For a keyboard layout of Turkish language, there are only two studies performed so far. First layout was developed in 1955 by İhsan Sıtkı Yener who is a typist trainer. The name of his layout is "The Turkish F keyboard layout". This layout is an original design

developed based on the Dvorak's design principles. However, it still possesses the drawbacks of Dvorak layout which is detailed in the following sections. The Turkish F layout is designed only for writing faster according to the letter frequencies in dictionaries of 1950's. Turkish F keyboard was standardized in 1955 and the layout has been a requirement for imported typewriters since 1963. The second layout is developed very recently by Soydal as a master thesis under the supervision of Ekşioglu (2010) for a virtual keyboard requiring single finger or stylus text entry. Their layout indicates better performance results than F and Qwerty layouts. However, this layout considers only single finger or stylus text entry but not touch typing.

Therefore, this current study involves developing a methodology for an ergonomic and optimal keyboard layout that can be used in any language for touch typing considering ergonomics and efficiency criteria that is, decreasing fatigue induced by typing, increasing typing comfort and typing speed. In addition, the study involves developing an optimal and ergonomic keyboard layout for Turkish language using the developed methodology.

2. LITERATURE REVIEW

Before the methodology and the application of the methodology to Turkish language, one must gather some knowledge about touch typing, keyboards, keyboard layouts. In this chapter, the necessary knowledge to better understand the current work is presented.

2.1. Overview

Since the times of 1930's, there have been studies about keyboard layouts. One of the first studies is the study of Dvorak *et al.* (1936) who has shown the weaknesses of Q layout and proposed a new one. Many other studies followed until now while using different techniques for developing keyboard layouts.

There were also studies about the mechanism of touch typing. In these studies, a better knowledge of the technique is established and some rules for developing good keyboard layouts were defined. For instance, the fact that tapping with alternating hands are faster is uncovered with many more.

Through the transition from typewriters to electronic keyboards, several different keyboard types and alternative input methods were also proposed. However, until now none can take the place of conventional keyboards.

There were also studies about the health problems related with typing such as carpal tunnel syndrome.

In this chapter, some of these important studies are summarized so that the current work is can be more understandable and easy to be read.

2.2. Keyboard Types or Alternative Input Methods

Although most of the users use conventional keyboards, there are other keyboard types which have some advantages and disadvantages compared to the conventional

keyboards. In this chapter, these keyboard types are explained briefly.

2.2.1. Conventional Keyboard

In computing, a keyboard is a typewriter keyboard, which uses an arrangement of buttons or keys, to act as electronic switches (Figure 2.1). Despite the development of alternative input devices, such as the mouse, touch screen, pen devices, character recognition and speech recognition, the keyboard remains the most commonly used and most versatile device used for direct input into computers.

A keyboard typically has characters engraved or printed on the keys and each press of a key typically corresponds to a single written symbol. However, to produce some symbols requires pressing and holding several keys simultaneously or in sequence. While most keyboard keys produce letters, numbers or signs, other keys or simultaneous key presses can produce actions or computer commands.



Figure 2.1. Conventional keyboard.

In normal usage, the keyboard is used to type text and numbers into a word processor, text editor or other program. A computer keyboard distinguishes each physical key from every other and reports all key presses to the controlling software. Keyboards are also used for computer gaming, either with regular keyboards or by using keyboards with special gaming features, which can expedite frequently used keystroke combinations. A keyboard is also used to give commands to the operating system of a computer.

2.2.2. Chord Keyboard

On a chord keyboard, like chords in music, each letter has a specific key combination. This combination can be a single key or a combination of simultaneously pressed keys. These keyboards can be single handed or two handed (Figure 2.2).

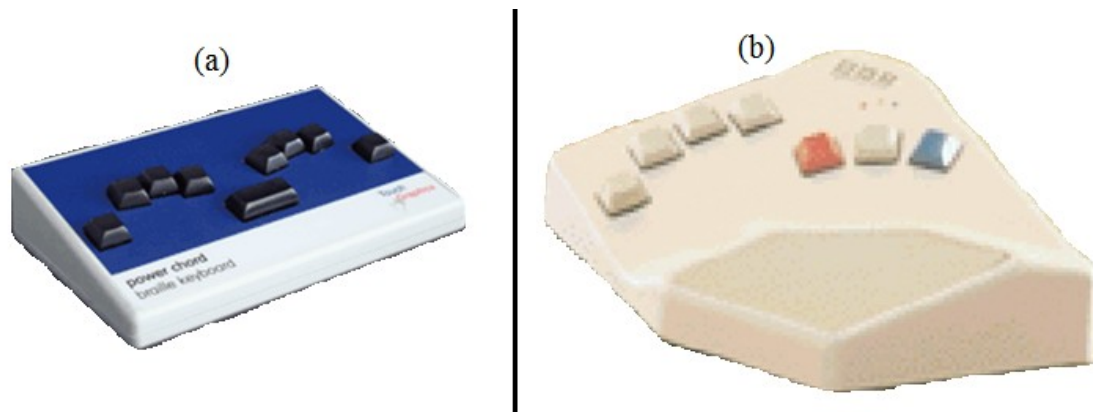


Figure 2.2. a. Two handed chord keyboard, b. Single handed chord keyboard.

Gopher and Raij (1988), Kroemer (1992) and McMulkin and Kroemer (1994) studied the productivity of chord keyboards relative to conventional keyboards and chord keyboards have been suggested as fast as conventional keyboards.

A chord keyboard has some advantages and disadvantages. Its most important advantage is from an ergonomic point of view since you don't need to move your wrists or fingers over keys to type. This reduces the risk of carpal tunnel syndrome. Also it has an option of using one or two hands. The other advantage is its relatively small size which increases its portability and usage in hostile environments.

Its basic disadvantage is the need to memorize key combinations. However, Ratz and Ritchie (1961) concluded the additional time required to memorize operation combinations of a chord keyboard is repaid by the gain in the outputs.

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 hours.

However, users still prefer conventional keyboards over the chord keyboards because of the additional time required for memorization of the combinations before using these keyboards.

2.2.3. Keybowl

The Keybowl keyboard was developed to especially accommodate handicapped users. It eliminates finger movement but increases wrist movement.

The Keybowl (Figure 2.3) is an alphanumeric input system which uses a pair of bowls, upon which the hands rest, coupled to a base. The Keybowl has a 64 character capability (an 8 by 8 design). Both hands are used to type characters, one hand per bowl. First bowl which moves in eight directions is used to activate the different character rings on the other bowl. The character rings contain eight characters each defined by a discrete movement of the bowl. Each bowl moves into the same 8 compass rose directions. The eight position bowl used for typing the characters will be used by the user's dominant hand.

The Keybowl typing methodology entails creating a keystroke via a combination of positions of the two bowls. For instance, referring to Figure 2.3, moving the left-hand bowl to the "hatched" position enables access to the "hatched concentric circle" of the right-hand bowl. Once a position on the selector bowl is selected the characters on the character bowl can be typed by moving the right bowl into the character position that the user wishes to type. The lateral movements of bowl is the same for all characters (i.e., characters on the outer character rings require the same lateral displacement as those on the inner ones).

There are no extensive studies on this type of keyboard. However, this keyboard type increases the wrist deviations and movements a lot. Also the typing speed is slow compared to conventional keyboards.

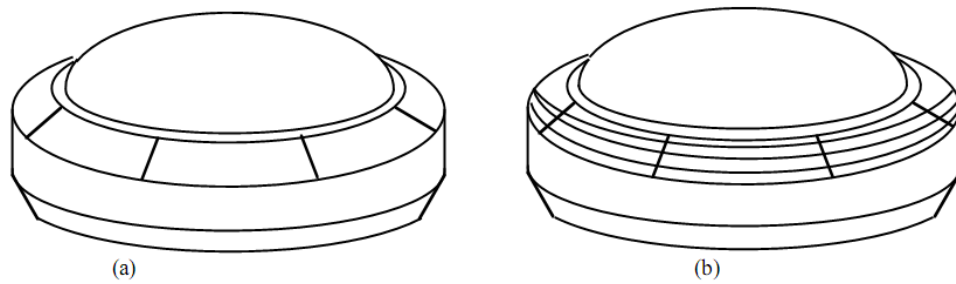


Figure 2.3. The Keybowl (profile view).

2.2.4. Multi Character Keyboards

The multi-character keyboard arranges more than one characters on a single key, this design is used to facilitate language production using a telephone keypad whose working area is smaller than that of a standard keyboard and so it affords a fewer number of keys (Figure 2.4). To disambiguate each key, the first proposal simply groups the letters alphabetically and requires the typist to produce a single letter by two keystrokes. The first keystroke selects the group the target letter belongs to, and the second chooses the letter index in that group.

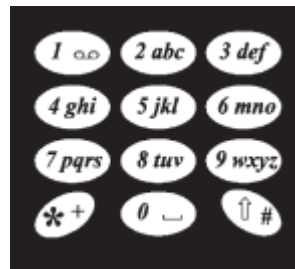


Figure 2.4. A well known multi character keyboard that is often used in mobile phones.

This keyboard type has lost most of its relevancy after the market is dominated by touch screen mobile phones and PDA's.

2.2.5. Virtual Keyboards

The scenario of using a single-finger keyboard (Figure 2.5) arises when typing with hand-held devices such as mobile phones or PDAs, using virtual keyboards displayed on touch screen, or when the user is motor-impaired and needs to use a point-based text entry

means. In these virtual keyboards, users have different styles. For instances; some of them use only their right index finger, some of them use their both thumbs, etc.



Figure 2.5. An example of virtual keyboards.

2.2.6. Speech Recognition

Speech recognition, which is probably the best user interface, is now at a stage where it can be successfully deployed in limited domains, such as in call centers for customer service or for voice dialing on mobile phones. Under these conditions, it provides a highly user-friendly, unobtrusive, flexible and efficient interface method. However, careful estimates suggest that 100% recognition rates for large vocabularies will not be possible in the near future. Noisy environments and speaker particularities (accents, speech impediments) worsen the situation (Kölsch and Turk, 2002).

Although the best interface; because of the technical limitations right now, speech recognition does not seem to replace the conventional keyboards in the near future.

2.2.7. Handwriting Recognition

Handwriting recognition is another interface that offers itself to human computer interaction. It is equally hard as speech recognition, especially connected-cursive handwriting. Just as in writing on plain paper though, the throughput is limited because a single actuator (the pen led by the fingers) is performing the serial task. One unit of

information, a character, consists of a combination of straight and/or curved lines and/or dots. The amount of information a human can output through the medium of a pen is limited by motor skills rather than by cognitive skills (Kölsch and Turk, 2002).

So the efficiency of the conventional keyboards is much higher than handwriting recognition method.

2.3. Keyboard Designs

Keyboard usage has some bad effects on the posture of the body. Some of these postural demands are related with the design of the conventional keyboard. In conventional keyboards, users experience ulnar deviation of the wrists, wrist extension, forearm pronation and shoulder abduction (Rempel, 2008).

In order to overcome the ergonomic deficiencies of the conventional keyboard geometry, some keyboard designs were proposed. In a publication by NIOSH (1997), these alternative keyboard designs are summarized. In this chapter, these keyboard designs and their possible effects on the ergonomics of the typist are summarized.

2.3.1. Split Keyboards

Split keyboards are designed to straighten the wrist and to reduce ulnar deviation of the wrists (Figure 2.6). This can be done in two ways: by increasing the distance between the right and left sides of the keyboard or by rotating each half of the keyboard so that each half is aligned with the forearm. Some alternative keyboards combine these two methods.

Built-in wrist or palm rests help prevent bending the hands up by providing support that straightens the wrists. It should be noted that questions do remain about the usefulness of wrist or palm rests. For example, it is unclear whether they increase pressure on the wrists, relieve loads on shoulder and upper back muscles, or interfere with typing.

Split keyboard configuration is more comfortable, increases relaxation and decreases fatigue of the arms and hands while typing (Lincoln *et al.*, 2000). On the other hand, the

problem of wrist-extended posture is still present (Hedge and Powers, 1995). Also, the additional width requires the VDT user to place the mouse in a position that will require elevated arm abduction (Harvey and Peper, 1997).



Figure 2.6. Split and rotated keyboard with wrist rest.

2.3.2. Tented Keyboards

On tented keyboards, the two keyboard halves are tilted up like a tent (Figure 2.7). This feature is a variation of the split keyboard and reduces the pronation of the forearms. Although the logic behind the design seems good, more studies are needed investigating the design and efficiency of tented keyboards.

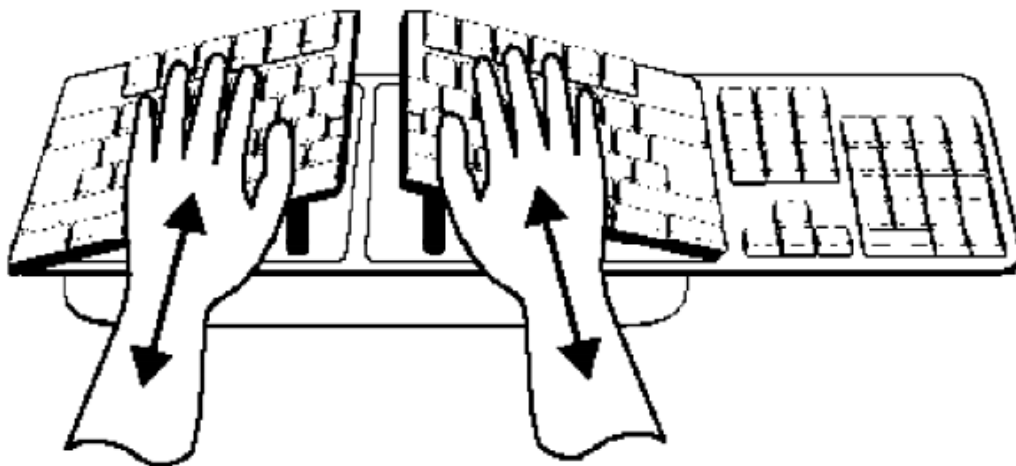


Figure 2.7. Split and tented keyboard.

2.3.3. Keyboards with Negative Slope

Keyboards with a negative slope (Figure 2.8) help prevent bending the hand too far up (wrist extension) by allowing the user to raise the front edge of the keyboard, or to slope the keyboard backward, thus straightening the wrist that eliminates the problem of wrist extension reducing it from 13° extension to 1° flexion (Hedge and Powers, 1995).

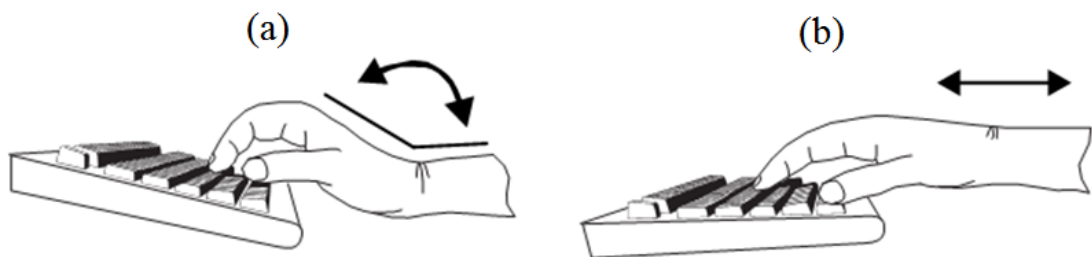


Figure 2.8. a. Conventional keyboard, b. Keyboard with negative slope.

2.3.4. Keyboards with Curved and Concave Key Positions

Some alternative keyboard designs have attempted to “fit” the different lengths of the fingers by curving the rows of keys or by placing the keys in concave wells (Figure 2.9). This is believed to allow the fingers to work in a more relaxed posture. However, more studies are needed investigating the benefits and efficiency of these type of keyboards.

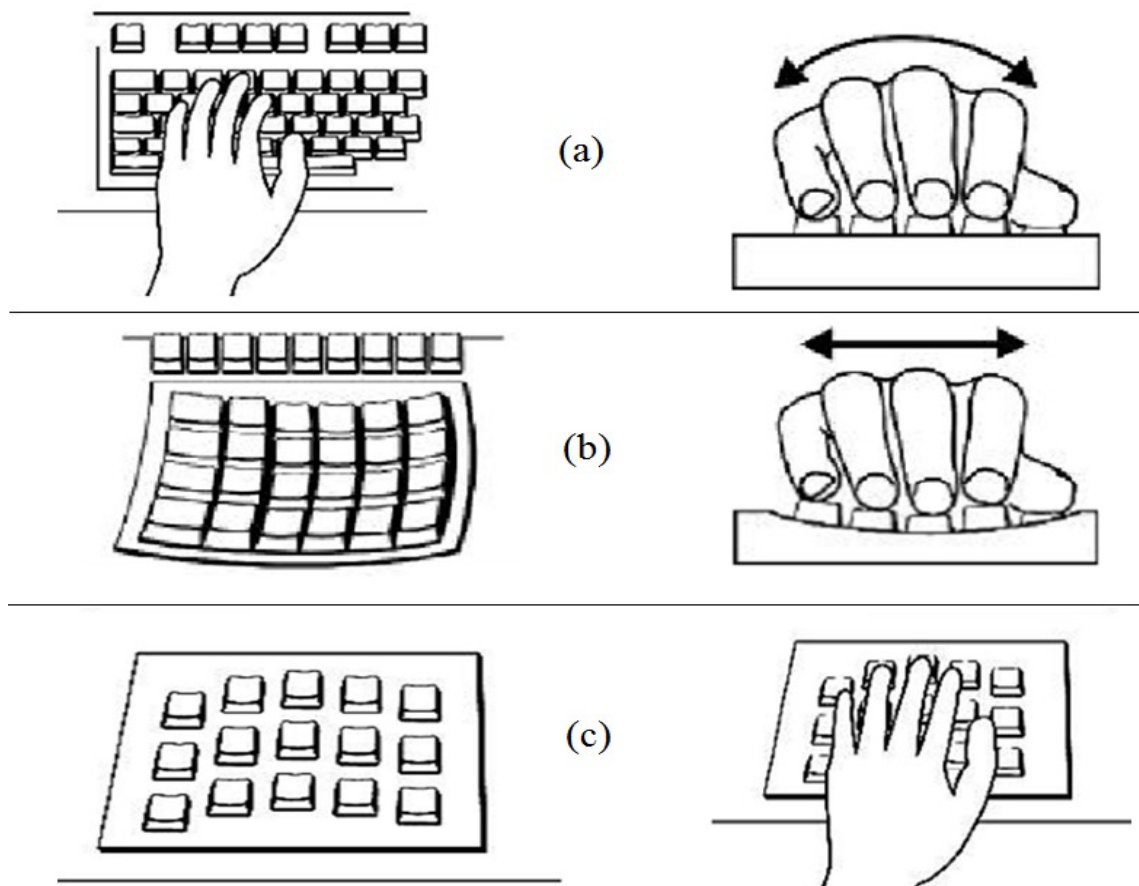


Figure 2.9. a. Conventional keyboard, b. Concave well keyboard, c. Curved keyboard.

2.3.5. Related Research on Alternative Keyboard Designs

Rempel (2008) reviewed the important studies on alternative keyboard designs in a very detailed review paper. His review provides the following: First, subjective preference may not be sensitive to ergonomic benefits for devices that are used repetitively but require low activation forces. Second, health benefits of ergonomic keyboards were not apparent in short term (2 to 5 day) studies of discomfort and pain but were observed only after 4 months of use. Third; in short term studies, ergonomic principles (e.g., the reduction of postural risk factors and muscle loads) resulted in positive health outcomes. Finally, the ideal keyboard design has not been identified yet; there is still much to be done on the geometry of the keyboard and keys. The history of the adoption of the split keyboard design is an unusual one in human factors research. Split keyboards are not associated with increased productivity – the main value is improved health.

The National Institute for Occupational Safety and Health (NIOSH) conducted a 2-year randomized controlled trial to evaluate the effects of different keyboard designs on pain and upper extremity disorders among 289 computer users (Moore and Swanson, 2003). Participants were randomized to receive a conventional keyboard, a fixed split keyboard, or an adjustable split keyboard. The study found that the fixed split keyboard prevented the occurrence of new symptoms in the neck region. Both split keyboards also reduced pain in the hands, wrists, and forearms among those computer users with pain at the beginning of the study. This study provides the strongest evidence to date for both a primary and secondary prevention benefit of the split keyboard on upper body musculoskeletal health.

Alternative keyboards have been thought to promote neutral wrist posture. Yet, available research does not provide conclusive evidence that alternative keyboards (except split design) reduce the risk of discomfort or injury. Thus, further research is needed before specific keyboard features can be recommended with great confidence (NIOSH, 1997).

Fagarasanu and Kumar (2003) enlist the possible alternative keyboard designs that can possibly reduce some awkward postures. These are shown in Table 2.1.

Table 2.1. Alternative keyboard designs that can possibly reduce the related awkward postures.

Awkward Posture	Keyboard Design Feature
Wrist ulnar deviation	Split design
Excessive wrist extension	Negative slope keyboard
Forearm pronation	Lateral inclination
Fingers stretching	Curved key rows (horizontal plane)
Fingers excessive flexion	Concave key rows (vertical plane)

2.4. Touch Typing

Touch typing is typing without using the sense of sight to find the keys. Specifically, a touch typist will know the location of the keys on the keyboard through muscle memory.

2.4.1. Basics of Touch Typing

At the time, typing competitions were organized in order to motivate typists to improve their typing skills, Frank Edward McGurrin, a court stenographer from Salt Lake City who taught typing classes, won a decisive victory over Louis Traub (operating calligrapher with eight-finger method) in a typing contest held in Cincinnati. In this competition, McGurrin used a technique that he developed himself called touch typing (typing using ten fingers). McGurrin won \$500 (\$11,400 in 2007) and popularized the new typing method. His victory was the beginning of modern dactylography and as such plays a vital part in keyboard layout designs (Seamans and Benedict, 1900).

Touch typing typically involves placing the eight fingers in a horizontal row along the middle of the keyboard (the home row) and having them reach for other keys. On a standard QWERTY keyboard the home row keys are: "asdfjkl;" Most computer keyboards have a raised dot or bar on F/J keys (or the keys in the same position, for non-QWERTY keyboards) which enables blind or partially sighted individuals to position their fingertips correctly over the home row, and this also incidentally helps sighted touch-typists to orient their fingers as well.

The most common other form of typing is "hunt and peck typing" (or two-fingered typing). They usually rely instinctively on the strongest fingers (the index and middle finger) and because they have their forearms positioned in midair to hunt all over the keyboard, they are less likely to develop CTS because of the absence of wrist fatigue and ulnar deviation (Fagarasanu and Kumar, 2003). However, this method is much slower than touch typing because instead of relying on the memorized position of keys, the typist is required to find each key by sight and move fingers a greater distance. Many idiosyncratic styles in between those two exist: for example, many people will type blindly, but using only two to five fingers and not always in a systematic way.

"Home row" is a term that refers to certain keys of the center row of alphabetical letters on a computer keyboard. On the QWERTY layout, "A S D F G H J K L ;" represents the contents of the home row. To touch type, one should place all of his/her fingers on the home row (The right hand should be covering "J K L;" with the thumb on

the space bar while the left hand covers "A S D F", Figure 2.10). Every finger has its assigned keys (Figure 2.11) and the fingers return to their standard positions occasionally after pressing any other assigned key that is not on the home row.

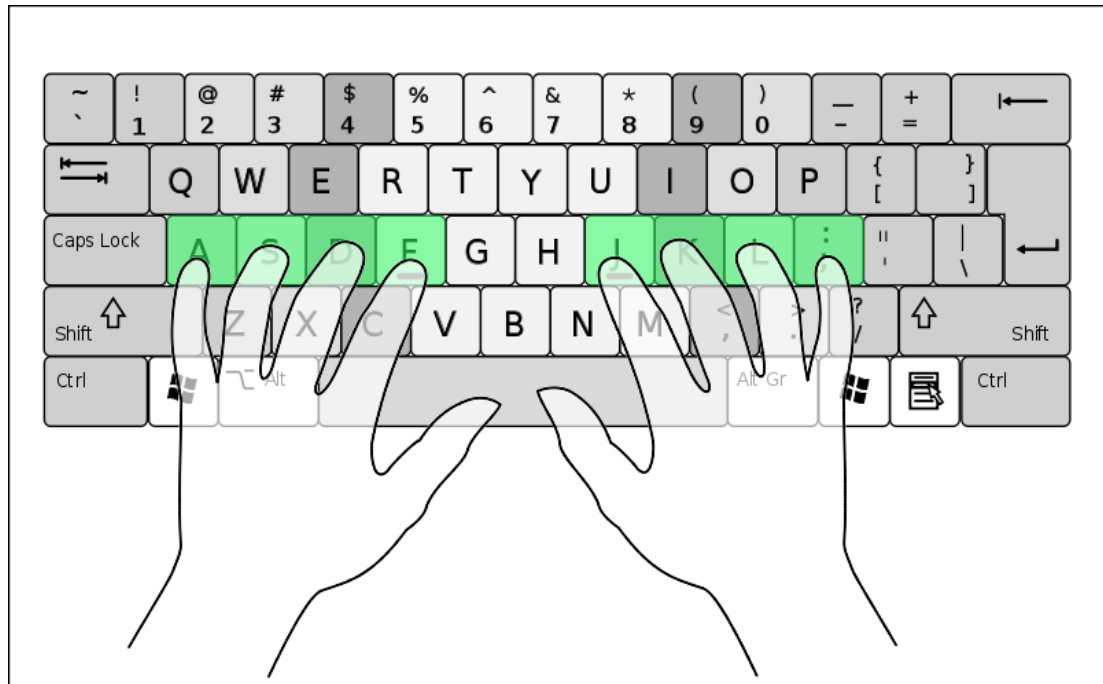


Figure 2.10. Starting positions of the fingers on a conventional QWERTY keyboard.

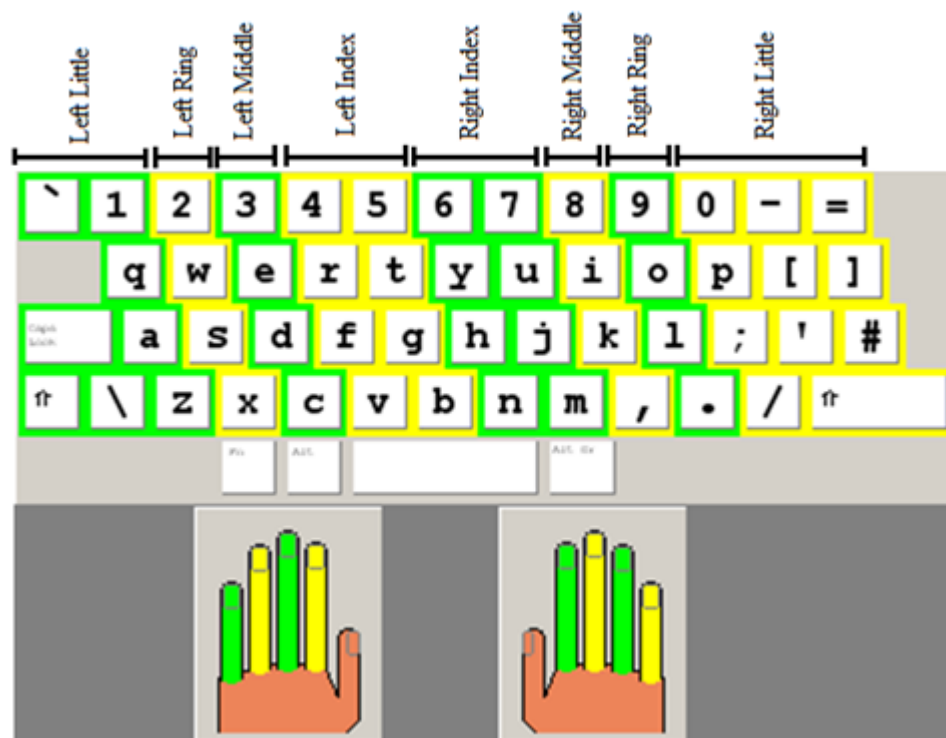


Figure 2.11. Finger allocation on a standard Q keyboard layout.

2.4.2. Mechanisms of Touch Typing

Touch typing is a parallel process, however if it would be a serial movement of fingers; for instance, to type the word “poll” on a QWERTY keyboard, the typist would then use his right little finger to reach for the "P" key located just above the semicolon and then return the little finger back to the semicolon key from which it originated. The right ring finger, located on the "L" key would be moved directly upwards to press the "O" key and then back. Finally, the same ring finger would remain on the "L" key and press it twice (see Figure 2.11).

However; touch typing is not a serial process which involves the movement of one finger at a time, rather contains an intricate and complex interaction of perceptual, cognitive, and motor processes. Not only does verbal material have to be registered and perceived, but it has to be appropriately partitioned, accurately translated into physical movements, and then those movements executed at rates exceeding several hundred keystrokes per minute. Experienced typists can do this at speeds of over 100 words per minute, but the method is that they always return their fingers to the home row when they are not in use. This provides for quick and easy access to all of the keys on the keyboard (Salthouse, 1986).

People can type very quickly. World champion typists can type at rates up to 200 words per minute. This involves a mean interval between keystrokes of 60 ms, close to the neural transmission time between the spinal cord and the periphery. Even an average professional typist operating at a rate of 60 gross words per minute produces five keystrokes per second (200 ms per response). These interkey intervals are only a small fraction of the typical choice reaction times. For example, a study by Salthouse (1984) reported that the median interkey interval in normal transcription typing was 177 ms whereas the median interkey interval for the same individuals in a serial two-alternative choice reaction time task was 560 ms. This is an extraordinarily fast time in the context of choice reaction time activities. This shows that typing is not a collection of simple serial movements of fingers.

The most rational explanation for typing performance considerably exceeding the limits of choice reaction time is that the various processing operations in typing overlap in time, whereas those in a choice reaction time task are necessarily serial because the following stimulus does not appear until the occurrence of the preceding response. That is, in normal typing it is assumed that the typist is executing one keystroke while simultaneously preparing the movement patterns for the next keystroke. These parallel operations are not possible in typical reaction time tasks and therefore the latencies in such tasks are the sum of the durations of all component processes instead of merely reflecting the durations of the last one or two processes, as in typing. This can be seen from Figure 2.12 which shows the timing of an example phrase while touch typing (Gentner, 1981).

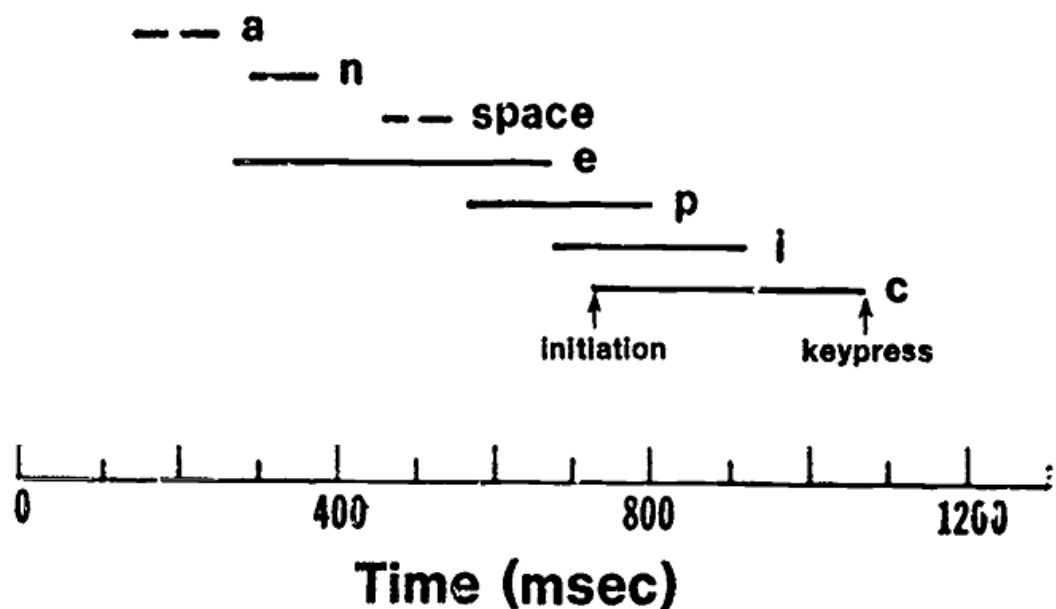


Figure 2.12. Relative timing of the keystrokes of the phrase "... an epic ..." by an expert touch typist. Start of the lines is the initiation of the keystroke while end of the lines show the exact time of the key press (from Gentner, 1981).

This phenomenon of parallel motions of hands over the keys, was also explained by Gentner *et al.* (1980) using a laboratory study. They have carried out a photographic analysis of a skilled typist using a high speed motion camera. The results of this study show the fingers of the hand in almost constant motion, with fingers starting to move toward their destination before the several preceding characters have been typed (see Figure 2.13). So they have concluded that a serial model of typing in which each finger in

turn makes its stroke is incorrect. Rather, there seems to be a coordinated structure that allows the control of several fingers simultaneously.

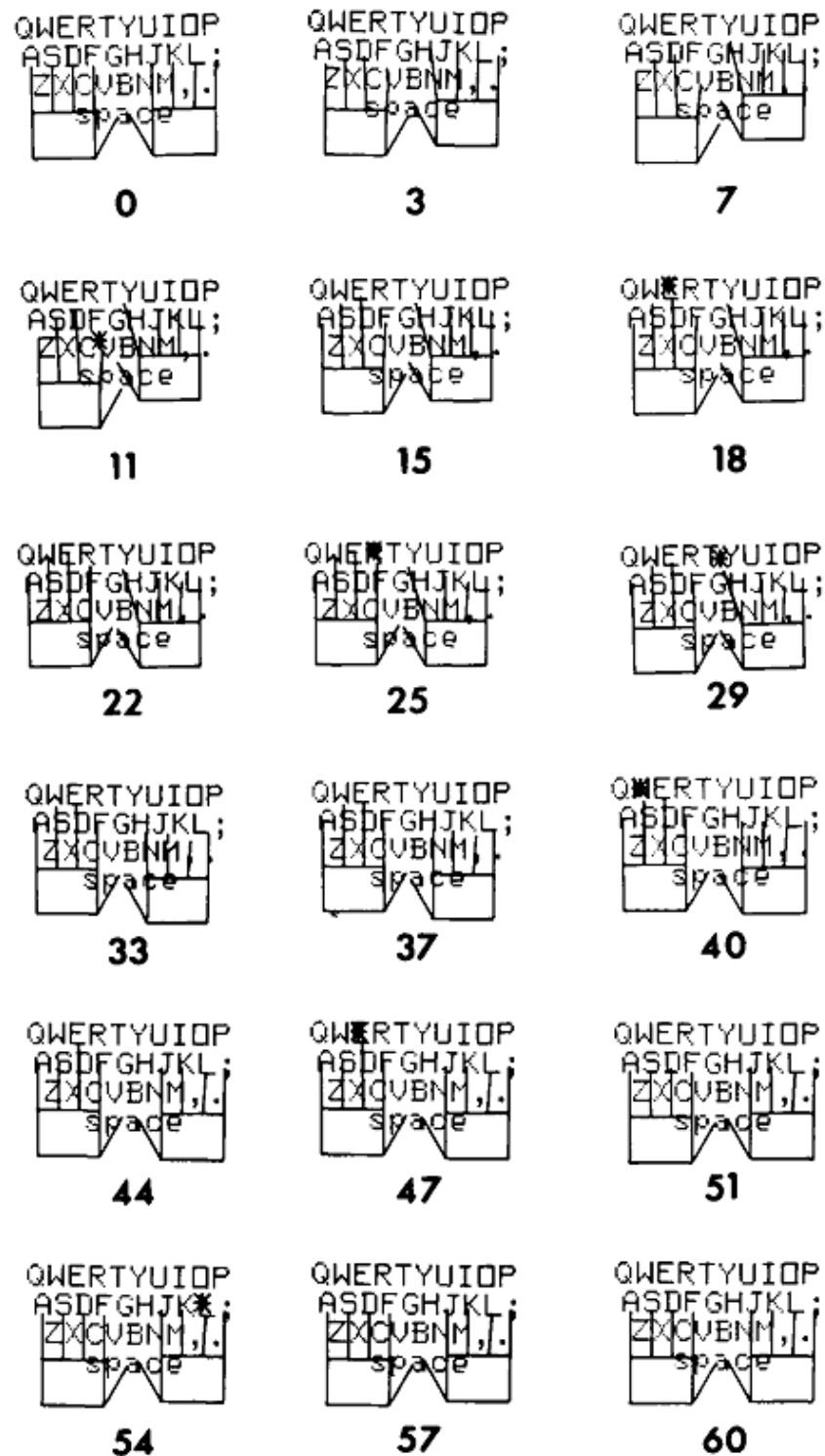


Figure 2.13. Hand and finger configurations photographed in the writing of the phrase “very wel”. You can see two hands of the typist. The fingers are shown using straight lines.

The * indicates an actual press of a key (from Rumelhart and Norman, 1982).

2.4.3. Factors Affecting Typing Performance (Interkey Interval Times)

There are a number of factors that affect the performance of typing, that is speed of typing, in other words interkey interval times. Interkey interval time is defined as the time that passes between two keystrokes and generally expressed in milliseconds. The factors that affect interkey interval time are explained below.

2.4.3.1. Replacement Span. The span that indicates how far in advance of the current keystroke the typist commits to a particular character is called as the replacement span and it is larger among more skilled typists. For professional typists, replacement span is approximately three characters in advance of the current keystroke. This inference is based on the results of a replacement span procedure introduced by Salthouse and Sauls (1985). Correlations between net words per minute and replacement span in the Salthouse and Sauls' (1985) two studies were 0.46 and 0.80 respectively (both p values < 0.01). Their regression equations indicated that the replacement span increased by about one character with every 30 net words per minute increase in skill. The mean replacement span values in these two studies were 2.79 and 3.04 respectively.

Several other studies have investigated the effect of replacement span using the context effects. They indicated that the maximum length over which context effects are evident in skilled typists is only two to three characters. Shaffer (1978) reported that the interkey interval for a given character was different when the character two keystrokes before the character was varied and the intervening characters were constant, suggesting that there was a context effect extending over at least three characters. However, his data were based on a single highly skilled typist and therefore the generality of this finding was unclear. Gentner (1982, 1983) considered a greater number of typists and more alternative contexts. He reported that the variability of interkey intervals appeared to decrease as the amount of prior context was increased from zero to two characters, implying that the context effect may extend to three keystrokes.

2.4.3.2. Alternating Hand Usage. Successive keystrokes from fingers on alternate hands are faster than successive keystrokes from fingers on the same hand. This is a very well-documented phenomenon, one that has been confirmed in numerous reports (e.g., Fox and

Stansfield, 1964; Gentner, 1981, 1982, 1983; Grudin and Larochelle, 1982; Kinkead, 1975; Rumelhart and Norman, 1982; Salthouse, 1984; Shaffer, 1978; Terzuolo and Viviani, 1980).

Typists of average ability are generally between 30 and 60 ms faster when the preceding keystroke was on the opposite hand than when the preceding keystroke was on the same hand. Many observers (e.g., Dvorak *et al.*, 1936; Gentner, 1981, 1983; Rumelhart and Norman, 1982; Terzuolo and Viviani, 1980) have interpreted this alternate-hand advantage by suggesting that with successive keystrokes on the same hand, there is little opportunity for advance preparation of following keystrokes, whereas when the opposite hand is involved in the preceding keystroke, the relevant finger can begin its motion toward the next key at the same time that the preceding key is being struck. Direct support for this view has been provided by Larochelle (1984) who found from analyses of videotape records that the initiation of a keystroke occurred 32 ms before the termination of the preceding keystroke for alternate-hand sequences but 39 ms after the prior keystroke for same-hand sequences.

Kinkead (1975) also conducted one of the most complete analyses about alternating hand movements and reported that keys struck with alternate hands averaged 136 ms; those with the same hand, 168 ms; and those with the same finger, 218 ms.

2.4.3.3. Other Factors that Affect Interkey Intervals and Variability of Interkey Intervals.

Digraph Frequency Effect: Letter pairs that occur more frequently in normal language are typed faster than less frequent pairs. This digraph frequency effect has been reported many times (e.g., Dvorak *et al.*, 1936; Grudin and Larochelle, 1982; Salthouse, 1984; Terzuolo and Viviani, 1980). A mechanism that may be responsible for these effects of frequency is more efficient overlapping and integration of translation and execution processes for highly practiced letter pairs. If you are familiar with something and do it over and over again, you become faster at doing that.

Word Initiation Effect: The first keystroke in a word in normal continuous typing is generally slower than other keystrokes in the word. This “word-initiation effect” has been reported by many authors, and was clearly documented by Salthouse (1984), where the

interval before the first keystroke in a word was found to be approximately 20% longer than the interval between the succeeding keystrokes in the word.

The time needed to type a specific character will vary in different contexts because the character: (a) is sometimes preceded by a keystroke on the alternate hand and sometimes by a keystroke on the same hand, (b) is sometimes preceded by a letter that produces a high-frequency digraph and sometimes preceded by one that produces a low-frequency digraph, and (c) is sometimes the first character in a word and other times is in an interior or terminal position within the word.

Skill Effect: Digraphs typed with two hands or with two different fingers of the same hand exhibit greater changes with skill than do digraphs typed with one finger. The explanation for this phenomenon seems to be that a large part of skill acquisition in typing consists of learning to overlap and coordinate the movements of successive keystrokes. Because overlapping is only possible with successive keystrokes made by different fingers, the absolute amount of improvement can be expected to be much greater for two-hand and two-finger digraphs than for digraphs made by the same finger (Salthouse, 1986).

The variability of interkey intervals decreases with increased skill of the typist. Two types of variability can be distinguished in typing, and both have been reported to be smaller among faster typists.

Intrakey Stroke Variability: One type of variability is intrakey stroke variability or repetition variability. This is the distribution of interkey intervals for the same keystroke in the same context, but across multiple repetitions. For instance, typing the same digraph 'ak' in different contexts and in different times. Average interquartile ranges for same-keystroke intervals are about 33 ms and decrease about 0.5 ms for every net word per minute increase in the overall speed. The correlation coefficient of the intrakey stroke variability and the typing skill is -0.71 (Salthouse, 1984) which means that with skill this variability decreases.

Interkey Stroke Variability: The second type is interkey stroke variability. This variability refers to the distribution of interkey intervals across different keystrokes and

different contexts. The inter quartile range of interkey intervals across all keystrokes typically averages between 70 and 80 ms for average typists, but correlates -0.69 with net typing speed, and decreases about 1.5 ms for every net word per minute increase in speed (Salthouse, 1984). In order to achieve the high rates characteristic of skilled typing, fast typists may be more consistent in their keying speed than less competent typists (Gentner, 1982; Long *et al.*, 1983). Fast typists somehow manage to reduce the time of what are initially slow keystrokes to nearly the rate of the fastest keystrokes.

To better understand the interkey stroke variability, the digraphs can be divided in twenty or more classes based on the nature of finger movement required for the transition, with the interkey stroke intervals for each digraph class showing significantly different performance and acquisition curves. However, the following division into four digraph classes provides a simple system that still captures the most significant distinctions holding across different typists (Salthouse, 1984).

- (i) One-finger double digraphs: Sequences of a single double key typed by a single finger such as “dd” in Q layout.
- (ii) One-finger non-double digraphs: Sequences of two different keys typed by a single finger such as “de” in Q layout.
- (iii) Two-finger digraphs: Sequences typed by two fingers on the same hand, such as “se” in Q layout.
- (iv) Two-hand digraphs: Sequences typed by different hands, such as “pe” in Q layout.

Means and standard deviations of medians in milliseconds for the four digraph categories across typists in Salthouse (1984) study are shown in Table 2.2. As seen in the table, one finger double takes less time than the others while one finger non-double takes the longest time.

The same categorization was used in nearly all the studies for interkey stroke times such as Heath and Wilcox (1990) and Gentner (1983). However, Hiraga *et al.* (1980) tried to drive a regression formula for all the digraph combinations.

Table 2.2. Means and standard deviations of medians for the four digraph categories across typists (from Salthouse, 1984).

Digraph Categories	Median			
	Study 1		Study 2	
	$\bar{x}$ (ms)	s (ms)	$\bar{x}$ (ms)	s (ms)
The fingers of two different hands	155	43	144	46
Two fingers of the same hand	194	45	185	51
One finger non-double	223	41	221	42
One finger double	176	26	168	22

There is also an autocorrelation effect in interkey stroke variability. Negative correlation between the intervals on successive strokes occurs especially when the successive strokes occur on alternate hands. Shaffer (1978) found that the autocorrelation with a lag of 1 (between strokes i and $i + 1$) was negative - that is, long intervals tended to be followed by shorter intervals and vice versa. However, the autocorrelation with a lag of 2 (between strokes i and $i + 2$) was positive.

2.5. Ergonomics Related Issues of Typing

Ergonomics related issues of typing can be classified into two folds: Health and performance. More explicitly, from the ergonomics point of view, an optimal keyboard layout should satisfy the following: minimizing fatigue caused by typing, maximizing typing speed, reducing the number of typing errors and allowing quick mastery of the typing method (Eggers *et al.*, 2003).

2.5.1. Typing Related Health Issues

Rempel *et al.* (1992) stated that more than 50% of occupational injuries result in strain injuries from overuse of hands. Also there is solid scientific evidence that intensive computing and fatigue over long run is associated with musculoskeletal problems, commonly known as cumulative trauma disorders (CTDs) (a type of musculoskeletal disorders), a phenomenon which is widespread among keyboard users. Ergonomists emphasize the role of three main risk factors that leads to CTDs: force, posture and repetition. Keyboard operations are a classical example, where these factors except force are extremely affecting the physiology of the operators (Gilad and Harel, 2000).

For the past 50 years, there has been increasing recognition and evidence that long hours of keyboard use are associated with hand, arm, shoulder, and neck pain and upper body musculoskeletal disorders (Gerr *et al.*, 2006). And one of the main problems that have been seen often in typists is the carpal tunnel syndrome (CTS).

2.5.1.1 Carpal Tunnel Syndrome (CTS). Lack of ergonomics design in computer workstations and its related human machine interface have been proved as the main cause to musculoskeletal illnesses; many of them are related to the carpal tunnel syndrome (CTS).

According to the U.S. Department of Labor, CTS affects over 8-million Americans. Among work related upper extremity disorders, CTS has the biggest impact in the professional computer users' health and in the industrial-related medical and non-medical costs. In United States alone, approximately 260,000 carpal tunnel release operations are performed each year, with 47% of the cases considered to be work-related (National Center for Health Statistics, 2000). From the 37,804 cases of work-related CTS reported in 1994, 7897 (21%) were attributed to repetitive typing or key entry data (Szabo, 1998).

There is a loss of productivity in typing jobs before, during, and after (days of hospitalization) the treatment of CTS (Moore, 1992). CTS which is the most commonly reported nerve entrapment syndrome (Silverstein *et al.*, 1987) results in the highest number of days lost per case among all work-related illnesses (Mani and Gerr, 2000). Almost half of the carpal tunnel cases resulted in more than one month work loss (National Center for Health Statistics, 2000). The overall cost of CTS is between \$20,000–\$100,000/hand (Szabo, 1998). Up to 36% of all CTS patients require life-long medical treatment, so the total costs are enormous.

Buckle (1997) described mechanisms for CTS: stretching or compression of the median nerve at the wrist, ischemia and increased intra carpal pressure when the wrist is in extreme postures. The most important factor in the CTS pathogenesis for keyboard and mouse users is the Carpal Tunnel Pressure (CTP). CTS patients have elevated CTP compared to healthy population (Keir *et al.*, 1998). During typing the hand and wrist adopt awkward postures that increase CTP exceeding the upper safe limit.

When the tasks require wrist extension, the ulnar or radial deviation cannot be extreme because there are limitations of movements in this plane during wrist extension. However, hazardous positions at a lesser value of ulnar/radial deviation when the wrist is in extension are likely to appear (Marshall *et al.*, 1999). The ulnar deviation that occurs during typing on a conventional keyboard, if it lasts for a prolonged period of time, is an important factor in the CTS pathogenesis.

During typing, which is a highly repetitive task; the adjacent tendons are sliding one against the other (see Figure 2.14). Velocities during typing in flexion/extension plane are similar to velocities in workers involved in industrial activities with great risk for CTS (Serina *et al.*, 1999). Nelson *et al.* (2000) used opto-electric wrist and finger monitors and the regression equations of Armstrong and Chaffin (1978) to calculate the tendon travel of fingers while typing to compare a number of keyboards with varying keyboard angles. They concluded that on average, the tendon travel for 1 h of continuous typing ranged from 30 to 59 m. Repetitive sliding of tendons within their sheaths will increase the friction that is a major trigger for the disorders of the tendons, their sheaths or adjacent nerves (Moore, 1992) and many authors (Yamaguchi *et al.*, 1965; Phalen and Kendrick, 1957) stated that the median nerve is compressed by thickening of the flexor tendon sheaths.

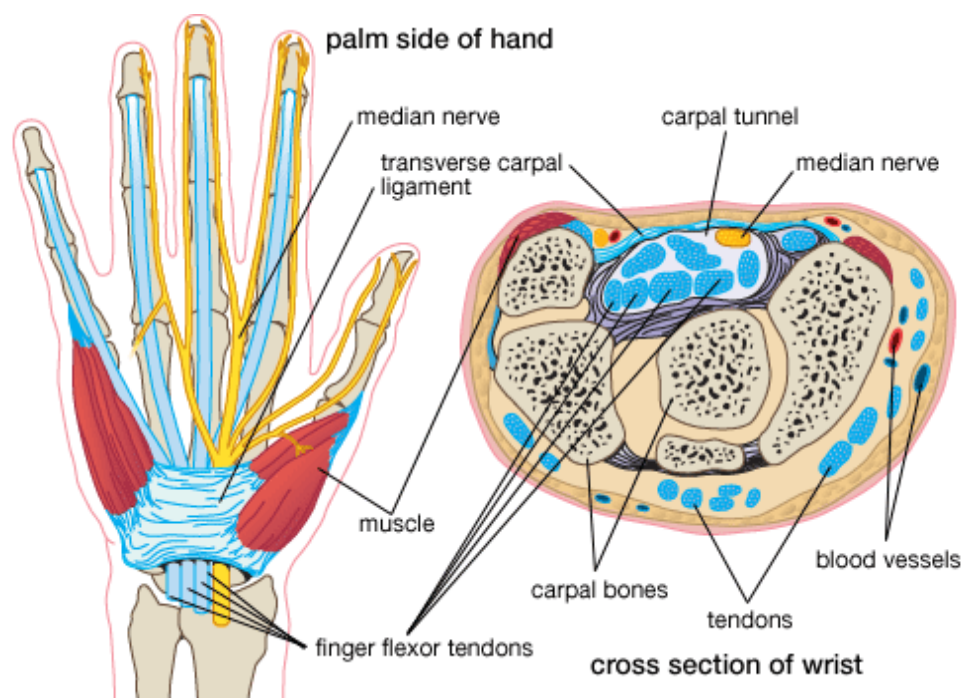


Figure 2.14. Hand anatomy.

Fingers undergo stresses in stretching for keys relatively far from their typing area. Overloading of the weakest fingers and a high number of keystrokes also increase the risk of CTS (Fagarasanu and Kumar, 2003).

Flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) (Figure 2.15) are the only muscles involved in flexion of all four fingers (Nelson *et al.*, 2000). The over use of these muscles and their tendons may lead to inflammation of the tendon sheaths (Marklin and Simoneau, 2001) and a reduction in the relative space which is the area that is available for the median nerve.

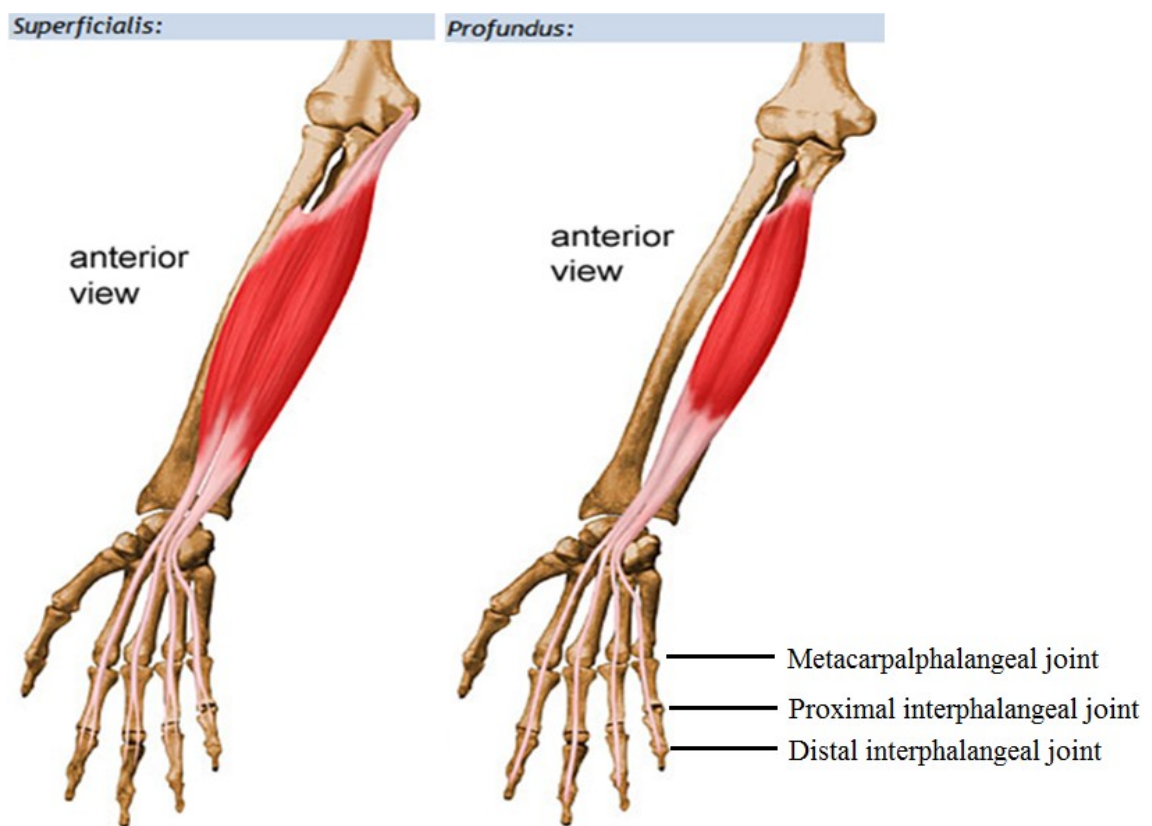


Figure 2.15. Flexor digitorum superficialis (FDS) and Flexor digitorum profundus (FDP) muscles.

Hence, tendon travel is an important factor in the pathogenesis of CTS. Tendon travel is calculated as a function of the keyboard design, standardized to unit time. Earlier research has shown how joint motion can be translated into tendon travel. Armstrong and Chaffin (1978) have shown that the displacement of the FDP and FDS could be obtained once the data were normalized for joint tendon thickness. Their regression equations can be

used to calculate tendon travel for the FDP and FDS. Similarly, it has been demonstrated that the tendon excursion for the extensor digitorum communis tendon can be predicted from the motion of the PIP and MP joints of the finger (An *et al.*, 1983).

To conclude, high repetition, unnatural postures of hand and wrist (e.g., wrist extension, ulnar deviation) and excessive force are the main risk factors for CTS. Two of these risk factors (high repetition and unnatural postures) exist in typing. This makes typing a risky task for CTS. Besides, excessive finger motions are also a risk factor for tendinitis (inflammation of tendons) and tenosynovitis (inflammation of tendon sheaths). For more detailed information about CTS related with keyboarding and mouse tasks, one can review Fagarasanu and Kumar's (2003) excellent review.

2.5.1.2. Other Musculoskeletal Issues. Although CTS is the first medical issue that come to mind regarding typing tasks, besides CTS there are other musculoskeletal problems caused by the awkward postures experienced in long durations of the use of keyboards and computers. For the past 50 years, there has been increasing recognition and evidence that long hours of keyboard use are associated with hand, arm, shoulder, and neck pain and upper body musculoskeletal disorders (Gerr *et al.*, 2006). These problems are related to work organizational issues (e.g., hours of computer use per day, job demands) as well as sustained awkward postures, such as shoulder elevation, wrist ulnar deviation, and head rotation. Some of these awkward postural elements can be reduced by keyboard geometry as explained in Section 2.3 while others require radical design changes and habits during the computer use.

Besides these problems, tendinitis and tenosynovitis are other important musculoskeletal disorders that affect typists frequently.

2.5.2. Typing Performance Issues

Typing performance is a function of typing speed, typing errors and fast learnability of typing method.

There are several factors that can have an effect on typing performance. Some of them are typing habits, ergonomics of typing environment, typing duration, keyboard geometry and keyboard layout. Although this study is about the keyboard layout, to type both fast and without health problems one should consider all these factors. So first, a basic education on office ergonomics is a must and also the environment should be designed ergonomically. Besides these, of course, the typist should use a well designed keyboard with an appropriate layout on it.

2.6. Keyboard Layouts

Keyboard layouts are the positioning of the letters onto the keys in the keyboards. Universal keyboard layout that is used in all over the world is the Q layout with its adaptations of several languages. In this section, some of the important keyboard layouts are discussed with their advantages and disadvantages.

2.6.1. Overview

Keyboard layouts have been studied since the early 1900's. After the first typewriter that was developed by two Americans, C.L. Sholes and C. Glidden became a commercial success, the keyboard layout that was used became a topic of debate since Q layout was a result of mechanical constraints that could not be solved at that time.

Many different keyboard layouts were proposed until now since Q layout is known to have some deficiencies. The most important of these layouts was the Dvorak layout (Dvorak *et al.*, 1936). Also for Turkish language, a layout called F layout was proposed in 1955 by İhsan Sıtkı Yener.

2.6.2. Q Layout

The original Q keyboard was intended for “hunt and peck” typing, not for touch typing. Breakthroughs like McGurrian's ten finger typing made the typists a lot faster and typewriters had to be improved in order to facilitate such fast typing. Finally, typists got so fast that typewriters often jammed and got broken. Unable to design better machines that

time, the keys were organized by the Sholes brothers in 1873 to minimize the jamming of type bars. They placed the keys that were typed successively as far apart on the keyboard as possible so that the type bars would approach each other at a relatively sharp angle, thus minimizing the chance of jamming. This rearrangement of the keys also made the typewriter harder to type. Ease of learning and typing were not considered (Noyes, 1983).

Q keyboard layout was deliberately designed to slow down typists and was dictated by mechanical constraints and these counter-optimized keyboards were justified for some decades during which mechanical problems remained in typewriters.

Also it appears to be a realistic assumption that Q layout is alphabetical in origin since D, F, G, H, J, K and L appeared on the home row. Q layout which was initially designed in an Anglophone context, were slightly rearranged later and thus adapted to other languages such as Turkish, French and German.

Noyes (1983) enlisted the disadvantages of the Q keyboard layout in his review. These are:

- It overloads the left hand. 57% of the typing is carried out by the non-preferred hand for the majority of the population. Of course, this proportion is only true for monograph frequencies in English language. According to the monograph frequencies in Turkish language; 47% of the typing is done using left hand in Q layout.
- It overloads certain fingers. For example, the little fingers are overworked to strike the shift, caps lock and backspace that is the heaviest key of all.
- It doesn't consider the force and dexterity of fingers. Table 2.3 shows the distribution of finger strokes on fingers in English (Ferguson and Duncan, 1974) and in Turkish using the monograph frequencies calculated for this study from Turkish National Corpus (Aksan *et al.*, 2012). It would be a natural assumption for the load to decrease from the index to the little finger since the force and dexterity (speed) of the fingers decrease from the index finger to the little finger (Table 2.4 and Table 2.5).
- Too little typing is carried out on the home row (32%). Consequently, too much (52%) of the typing is carried out on the top row and too little (16%) on the bottom

row. These proportions are also only true for monograph frequencies in English language. According to the monograph frequencies in Turkish language; 44%, 19% and 37% of the typing is carried out on the home, bottom and top rows respectively.

- Excessive row hopping is required in frequently used digraphs, often from the top to the bottom row, and bottom to the top row again. Digraph frequencies were not considered. By considering these frequencies, one can design a layout that can reduce awkward finger and wrist postures during typing.
- Many common words in English are typed using one hand. It doesn't consider the alternating hand writing.

It can thus be seen that the Q layout confers abnormalities of workload across the hands, fingers and rows while writing in both English and Turkish.

Table 2.3. The distribution of finger strokes on fingers in English and Turkish language on QWERTY layout (English: Ferguson and Duncan, 1974; Turkish: calculated for this study based on the study by Aksan *et al.*, 2012).

	Left Little	Left Ring	Left Middle	Left Index	Right Index	Right Middle	Right Ring	Right Little
English	8%	9%	19%	21%	19%	7%	14%	3%
Turkish	13%	3%	15%	16%	18%	10%	10%	15%

Table 2.4. Maximum finger pushing force (N) (Haaland *et al.*, 1963).

	Finger				
	Thumb	Index	Middle	Ring	Little
Average	165	107	98	80	53
Range	133-191	76-138	76-116	53-98	27-85

Table 2.5. Maximum tapping rate by hand and fingers according to Dvorak *et al.* (1936) and monograph experiment in the current study. (Tapping rates are given in taps / second. The details of the monograph experiments are explained in Section 4.5 and Section 5.1).

	Hand							
	Left				Right			
	Little	Ring	Middle	Index	Index	Middle	Ring	Little
Tapping Rate (Dvorak)	3.2	3.8	4.2	4.4	4.7	4.6	4.1	3.7
Tapping Rate (Current study)	2.8	3.1	3.3	3.3	3.7	3.7	3.6	3.3

2.6.3. Dvorak Layout

The Dvorak layout (Figure 2.16) was constructed in 1936 to be the optimal layout where "optimal" means "fastest". Dvorak studied letter frequencies and the physiology of people's hands and created a layout to alleviate the problems he identified with the QWERTY layout. It is worth noting that the Dvorak layout is more a set of principles to guide layout design than a certain keyboard (Nakic-Alfirevic and Durek, 2004). These principles are:

~ `	!	@	#	\$	%	^	&	*	(	)	{	}	← Backspace
Tab ⇐⇒	" ,	< ,	> .	P	Y	F	G	C	R	L	? /	+ =	 \ _
Caps Lock ⇧	A	O	E	U	I	D	H	T	N	S	- _	Enter ↵	
Shift ⇧	:	Q	J	K	X	B	M	W	V	Z	Shift ⇧		
Ctrl	Win Key	Alt								Alt Gr	Win Key	Menu	Ctrl

Figure 2.16. Dvorak layout.

- Consecutive letters should be typed by alternating hands which makes typing more rhythmic, increases speed, reduces error, and reduces fatigue.
- For maximum speed and efficiency, the most common letters and digraphs should be the easiest to type. This means that they should be on the home row, which is where the fingers rest, and under the strongest fingers (Thus, about 70% of keyboard strokes on the Dvorak Simplified Keyboard are done on the home row).
- The least common letters should be on the bottom row, which is the hardest row to reach.
- The right hand should do more of the typing, because most people are right-handed.
- Digraphs should not be typed with adjacent fingers. This is because of the preparation time for the next move as explained in Section 2.4. There is no preparation time if the digraph is pressed with the same finger. And also if the digraph is pressed with the adjacent fingers, the preparation time is small. However, if the digraph is pressed by remote fingers, the preparation time is greater; and it is greatest if the digraph is pressed with the fingers of the alternating hands.

- Stroking should generally move from the edges of the board to the middle. It is easier to drum the fingers from the little finger to the thumb than the other way around.
- Not all fingers are equally strong or equally fast: their speed and agility decreases from the thumb to the little finger.

The main key properties of the Dvorak layout are hand alternation, intensive middle row key usage and precedence of inner (index and middle) fingers over outer (ring and little) fingers.

A key property of most languages is the alternation between vowels and consonants: a property that played the key role in the design of the Dvorak layout. This is very important for rapid typing since as described in Section 2.4, using alternating hands is naturally faster and easier. This means that vowels can be grouped under one hand and the most frequent consonants under the other to make the basis for a very fast typing mechanism. Another detail of the Dvorak layout is the special attention to index fingers. Although other fingers except the right little finger normally cover only three keys, index fingers cover 6 keys each. So their keys must be a little less frequent to compensate such a heavy load. That is the main reason that not very frequent letters U and H are placed under the index fingers.

During the period 1931-1935, Dvorak and Dealey experimented extensively with the new keyboard. However no details of these studies were published and this has led individuals to doubt the superiority of the Dvorak Simplified Keyboard.

Dvorak layout is formed using a set of principles that are true for touch typing; however there is no specific algorithm behind it to develop an optimal keyboard layout and also no mathematical model and optimization procedure is used in the formation of this layout to optimize the overall criteria.

Many authors used finger travel distances to compare Dvorak layout with Q layout. Dvorak distances were regularly found to be greatly less than Q layout distances (e.g., 37% less in Ober's 1993 study). However, the assumption by Dvorak keyboard enthusiasts that differences in finger travel equal to or closely approximate the 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 (West, 1998). As described in Section 2.4, touch typing is a highly skilled process which involves parallel finger movements.

There are also some studies that keyboard layout is not as important as it seems in the context of typing speed. For instance, Kinkead (1975) concluded that the standard Q layout was operated during touch typing at near maximum speeds. He made an analysis of keying times and concluded that an imaginary optimal (in speed) layout using a higher percentage of fast keystrokes would be only 8% faster. Norman and Fisher (1982) reported that estimates of actual performance ranged from no significant differences to between 5 and 10% superiority in speed for the Dvorak keyboard.

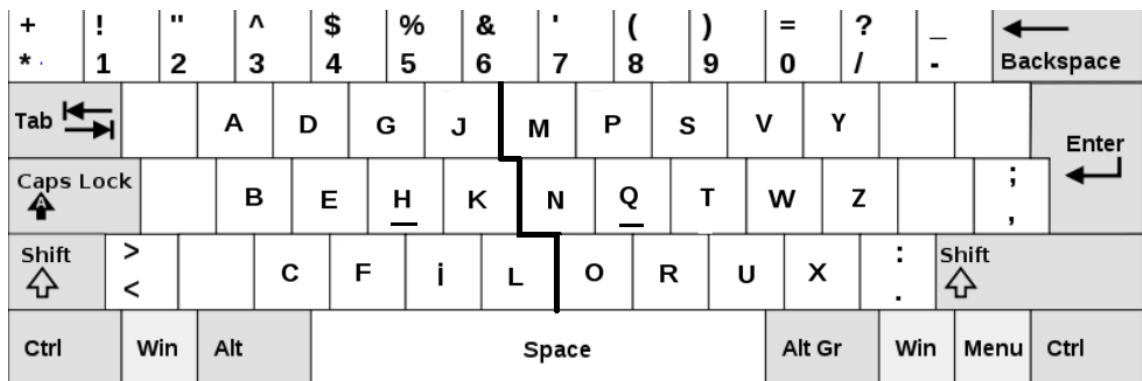
2.6.4. Alphabetical Layout

It seems a logical assumption that the alphabetical arrangement of keys (Figure 2.17) is superior to any other layout for novices since the knowledge of the alphabet would aid in finding the keys on the keyboard, thus enhancing typing speed and reducing mental workload for the novice. And most people think like that. However, studies of alphabetic keyboards fail to support this view; novice typists type as rapidly on the Q layout as on alphabetically organized keyboards (Hirsch, 1970; Michaels, 1971; Alden *et al.* 1972). These studies seem to contradict with the common sense.

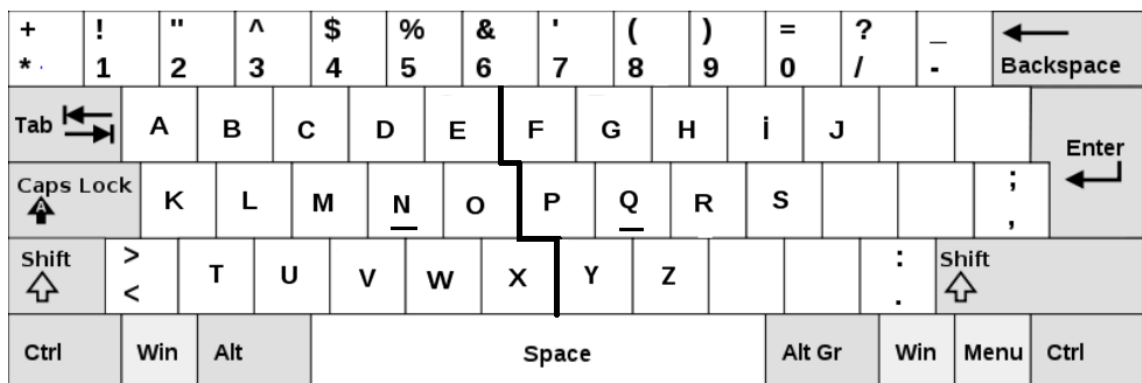
Norman and Fisher (1981) investigated the use of alphabetic layouts. In their study, everyone agreed that alphabetical arrangement seemed more rational, but they did not seem able to use the alphabet in their typing. It was surprising for everyone to discover that the alphabetic arrangement of the keys did not appear to help.

For example; suppose that you are typing the word “flower”. If you are using a horizontal alphabetic keyboard, the “f” is located on the front row, near the middle of the keyboard; where should you look for the “l”? Knowledge of the alphabet indicates that the “l” is after the “f”, and so perhaps you should look to the right to find it. But whether or not this is true depends upon where the linear string of the alphabetic is broken to fit it on the

keyboard. In fact, on this keyboard you must look to the left to find the “1”. Knowledge of the alphabet does not correspond to knowledge of key location. Thus, a simple analysis of the alphabetic layout indicates that the alphabetical arrangement is not so useful after all.



(a)



(b)

Figure 2.17. a. Diagonal alphabetical keyboard layout, b. Horizontal alphabetic keyboard layout.

Now consider using the diagonal alphabetic layout. This "diagonal" arrangement of the letters allows position in the alphabet to guide placement of the keys. In the word “flower”, “l” occurs both later than “f” in the alphabet and to the right of it on the keyboard. The correlation between the position of the letter in the alphabet and the location of the key is considerably higher for the diagonally organized alphabetic keyboard than for the horizontally organized keyboard. This keyboard arrangement should therefore be better than the horizontal arrangement. However, the informal observations of Norman and Fisher (1981) didn’t support this outcome either.

Norman and Fisher (1981) also made a study investigating the learning curves of Q, horizontal alphabetic, diagonal alphabetic and a random keyboard using 12 undergraduate students. These were novice typists. They concluded that there appears to be no differences between the learning rates of the two alphabetical arrangements, and the learning of the random keyboard is greater than that of the alphabetic, contrary to expectations. Hirsch (1970) and Michaels (1971) also conducted experiments related with alphabetical keyboards and none found results that support these layouts. So it seems that alphabetic layouts are not useful for novice typists.

For expert typists, key positions are memorized, so there will be no advantage of alphabetical keyboards. Besides, they confer abnormalities of loads on fingers.

2.6.5. Turkish F Layout

The Turkish F keyboard layout (Figure 2.18) is an original design with Dvorak's design principles. It was designed in 1955 by İhsan Sıtkı Yener who is a typist trainer. For its design, the dictionary of Turkish Language Institution (in Turkish, Türk Dil Kurumu (TDK)) with 29,934 words (of that time period) was investigated to calculate the letter frequencies in the Turkish language with the aid of TDK. F keyboard was standardized and the layout has been a requirement for imported typewriters since 1963.

+ *	! 1	" 2	^ 3	\$ 4	% 5	& 6	' 7	(8	) 9	= 0	? /	- .	← Backspace
Tab ⇐⇐	F	G	Ğ	I	O	D	R	N	H	P	Q	W	↵ Enter
Caps Lock ⇧	U	İ	E	A	Ü	T	K	M	L	Y	Ş	X	
Shift ⇧	> <	J	Ö	V	C	Ç	Z	S	B	:	;	Shift ⇧	
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl

Figure 2.18. Turkish F keyboard layout.

With this layout, Turkey has broken 14 world records in typewriting championships between 1957 and 1995. F keyboard layout is most commonly used by an older generation who learned this layout, because it is no longer taught in schools. Especially, companies

and government agencies having old technology still use this layout.

Digraph frequencies were considered by putting vowels in the left side and most common consonants to the right side. In Turkish language, mostly a consonant is followed by a vowel. By using that method, alternating hand movements which increases speed and reduces fatigue is maintained.

F layout is an adaptation of Dvorak principles to Turkish language and it still possesses the drawbacks of Dvorak layout. There is no scientific study in the open literature available today that describes the scientific methodology, if exists, behind the development of F layout. Besides, calculation of the frequencies in the design depends on the dictionaries of TDK in 1955. So the validity of these frequencies is also questionable.

In F layout, 49% of the typing is carried out by left hand. This proportion is true for monograph frequencies in Turkish language that are calculated from Turkish National Corpus (Aksan *et al.*, 2012).

It doesn't consider the force and dexterity of fingers. Especially, left and right index fingers are overloaded. Nearly half of the typing is done with two index fingers. Table 2.6 shows the distribution of finger strokes on fingers according to Turkish language. This distribution is not according to the tapping rate capacity of the fingers that are calculated in Section 5.1.2.

58% of the typing is carried out on home row. 30% of the typing is on top row and 12% on bottom row. These proportions are for monograph frequencies in Turkish language that are calculated for this study from Turkish National Corpus (Aksan *et al.*, 2012).

Table 2.6. The distribution of finger strokes of fingers on F layout in Turkish Language calculated from the monograph frequencies in Turkish National Corpus.

Left Little	Left Ring	Left Middle	Left Index	Right Index	Right Middle	Right Ring	Right Little
4%	11%	12%	22%	24%	14%	7%	6%

2.6.6. Other Layouts

There are many keyboard layouts that were designed by different designers for writing faster. Although their objective is generally the same (writing faster), these designers design their layouts using different perspectives. Some examples are below:

A Dutch designer Biegel (1934) developed a sequential keyboard which was a modification of the Q keyboard layout. He split the keyboard in half, so that the groups of keys are inverse images of each other, and placed the heaviest keys in the center. However, we do not have any success or failure data since this keyboard layout was not used in practice.

Ward (1936) allocated letters on his keyboard according to frequency of use. He attempted to center the hand and finger loads on the keyboard, and on the fingers with the greatest motor control. No experimental evidence has been found to support the Ward keyboard and it appears to have minimal interest amongst keyboard designers and researchers (Noyes, 1983).

Griffith (1949) designed the Minimotion keyboard with the aim of overcoming the defects of Q layout. Griffith's main design principle was to determine the optimum arrangement of letters for typing "average" English with the greatest possible ease. To achieve this, Griffith carried out a thorough analysis of the English language. Using a sample of 100,000 words, he performed a statistical analysis of word usage, single and adjacent letter usage and punctuation. This keyboard received little support although experimentally it has been demonstrated that slightly better keying rates than Q can be achieved (Stewart, 1973).

A similar approach was used by Maxwell (1953). He analyzed the 5000 most frequently used words in English and made his layout which he called as the Rhythmic keyboard. In this layout, he tried to assign maximum amount of work to the strongest fingers by making 44 changes to the Q layout. However, it soon became apparent that a perfect rhythmic setting would be impossible to attain by rearranging the Q layout.

Lillian Malt in conjunction with P.C.D. Limited designed the Maltron layout in 1976. This layout based upon an analysis of letter frequencies in 1,013,232 words (Kucera and Francis, 1967). 90% of the letters in the 100 most used words were placed on the home row, and similar rates were maintained for six other European languages. In the experiments in Basingstoke Technical College, a reduced learning time was demonstrated and reduced stress was also noted for the Maltron layout (Hobday, 1995).

2.6.7. Summary of Findings

Although many different keyboard layouts were proposed by different authors, none was successful to take the place of Q layout. The disadvantages of the Q layout were discussed in several papers, however despite its drawbacks it seems like changing the old habits needs a little more than that.

However, it is not true to claim that all other layouts were unsuccessful. Most of the touch typists in Turkey use Turkish F layout while many English touch typists use Dvorak layout. Although it is very difficult to change the universal keyboard layout for common users and maybe it is not necessary for them, it would be best for the touch typists to use the keyboard layouts that are designed for their language.

2.7. Methods for Keyboard Layout Generation

For developing keyboard layouts, different methods have been used. While most of the previous studies were using some heuristic rules, more recent studies are using optimization procedures to get an optimal keyboard layout.

2.7.1. Overview

In some developed layouts, the exact algorithm behind the generation procedure is not known. For instance in Dvorak's layout and F layout, it is known that there are some heuristic rules like alternating hand movement and heavy use of the home row; however, the exact algorithm, if exists, is not revealed. However; in some others, authors like Eggers *et al.* (2003) and Yin and Su (2011) focused on the keyboard development methodology

and algorithm more than the final layout. Below is a summary of some of the work that is classified by the algorithms used in the generation process. These methods can be categorized as heuristic methods and optimization methods. In optimization methods category, assignment model formulations and multi objective model formulations are used.

2.7.2. Heuristic Methods

In many early keyboard layouts, like Dvorak layout, the designers have some design principles such as home row usage, alternating hand movements, allocation of frequent keys to the strongest and fastest fingers, tapping direction, etc. These design principles aimed typing a text without fatigue, maximizing typing speed, reducing the number of typing errors, allowing rapid mastery of the touch typing.

For achieving these design criteria, they defined constructive heuristic methods. For instance; assigning vowels and consonants on different sides of the keyboard and assigning frequent letters to easily accessible key positions are most used constructive heuristic approaches. The most popular one among these is assigning the most frequent monographs to the home row using a specific rule. These rules generally consider the finger force and speed capacities; and left and right hand usage. Then letters are assigned to the bottom row, finally remaining letters are assigned to the top row using the same set of rules that are used for home row.

More recently, Marmaras and Lyritzis (1993) developed a new 8 step constructive heuristic for Greek language. In their constructive heuristic method, they defined low-load areas and easily accessed areas. In an iterative way, they assigned more frequent monographs to accessible areas. The criteria that they used to classify the areas were similar to the ergonomic criteria that were defined by Marsan (1976).

Some authors used evolutionary heuristics instead of constructive heuristics. In these heuristics, authors tried to optimize an existing layout like Q layout by making some changes on it. Martin (1972) developed a new keyboard layout by making changes on Q layout to adopt the advantages of Dvorak layout. Dasgupta *et al.* (2010) work on Q layout to get a new Bangla keyboard layout.

However, these methods are mostly insufficient in optimizing multiple objectives of a keyboard assignment problem at the same time.

2.7.3. Assignment Model Formulations

Another approach used by the researchers is using assignment model formulations which consist of linear assignment problem and quadratic assignment problem.

Keyboard layout optimization can be thought as an assignment problem since there are keys which must be assigned to certain locations. So, some of the authors (Pollatschek *et al.*, 1976; Light and Anderson, 1993; Nakic-Alfirevic and Durek, 2004; Malas *et al.*, 2008) used assignment model formulations to solve the keyboard layout optimization problem.

2.7.3.1. Linear Assignment Problem (LAP). Linear assignment problem involves the assignment of n people to n jobs. For each job assignment, there is a related cost, c_{ij} , of assigning person i to job j . The objective is to assign each person to one and only one job in such a manner that minimizes the sum of each assignment cost (total cost).

Mathematically, the Linear Assignment Problem can be formulated as follows (Taha, 2007):

$$\begin{aligned}
 \min. \text{Total Cost} &= \sum_{i \in \text{MONOGRAPHS}, j \in \text{KEYS}} \text{cost}_{ij} * x_{ij} \\
 \text{subject to} \\
 \sum_{j \in \text{KEYS}} x_{ij} &= 1 & \forall i \in \text{MONOGRAPHS} \\
 \sum_{i \in \text{MONOGRAPHS}} x_{ij} &= 1 & \forall j \in \text{KEYS} \\
 x_{ij} &\text{is binary} & \forall i \in \text{MONOGRAPHS}, j \in \text{KEYS}
 \end{aligned}$$

where KEYS is the set of all key locations on the keyboard and MONOGRAPHS is the set of all monographs (letters). cost_{ij} is the cost of assigning monograph i to key j and x_{ij} is the

binary decision variable that assigns monograph i to key j ($x_{ij}=1$, if monograph i is assigned to key j ; 0, otherwise). Notice that each set of assignments is a permutation of a set of n (number of keys) integers; hence, there are $n!$ distinct ways in which n monographs can be assigned to n key locations.

Some authors (Nakic-Alfirevic and Durek, 2004) used LAP for keyboard assignment problem. Cost of assigning a letter to a key position (c_{ij}) is calculated as the multiplication of the monograph frequency of the letter i and the distance of the key position j to the standard key position of the related finger.

However, this approach oversimplifies the typing process. It assumes typing as a serial process and assumes the related finger will return to its standard position before a consecutive finger movement starts. As shown in Section 2.4, this is not realistic. Typing especially touch typing is a highly skilled task that involves parallel finger movements.

2.7.3.2. Quadratic Assignment Problem (QAP). Optimization of locations of facilities in a network is a combinatorial problem called as Quadratic Assignment Problem (QAP) (Loiola *et al.*, 2006). Locations of clinics within a hospital, locations of warehouses in a nationwide logistics firm, or letter positioning in a keyboard layout can be found by mathematical models using QAP. This problem has been a focus of researchers for over four decades.

In other words, the quadratic assignment problem can be seen as a facility location problem. For example, assume that there are n facilities and n locations in a real life case. The pair wise flows between facilities and the distances between each pair of locations are known. The problem can be defined as assigning a facility to exactly one location such that the distance * flow is minimized.

Given a set of locations and facilities, and distance matrix between these locations and flow matrix between these facilities, the mathematical formulation that minimizes the (total distances * flows) is shown below:

$$\begin{aligned}
\min Total Distance &= \sum_{i,k \in FACILITIES, j,l \in LOCATIONS} flow_{ik} * Distance_{jl} * x_{ij} * x_{kl} \\
\text{subject to} \\
\sum_{j \in LOCATIONS} x_{ij} &= 1 \quad \forall i \in FACILITIES \\
\sum_{i \in FACILITIES} x_{ij} &= 1 \quad \forall j \in LOCATIONS \\
x_{ij} &\text{is binary} \quad \forall i \in FACILITIES, j \in LOCATIONS
\end{aligned}$$

Koopmans and Beckmann (1957) first proposed the QAP as a mathematical model related to economic activities. Since then, it has appeared in several practical applications such as electronics (Steinberg, 1961), economics (Heffley, 1972, 1980), facility location such as police posts, supermarkets, schools (Francis and White, 1974), scheduling (Geoffrion and Graves, 1976), even archeology (Krarup and Pruzan, 1978), etc. The examples cover a wide range from statistics to chemistry. And Pollatschek *et al.* (1976) was the first to apply QAP for finding the optimal keyboard layout.

The QAP is very useful to design a single finger keyboard such as virtual keyboards. Besides that it is also used to create physical keyboard layouts by some researchers (Malas *et al.*, 2008; Light and Anderson, 1993).

The flow between the letters is the frequencies of the digraphs in the related language. However, there are different opinions for distance matrix in literature although most of the authors used time intervals between specific key locations during touch typing. However, touch typing is a highly skilled task that involves parallel finger movements of both hands, so calculating a distance matrix is not easy. There are studies, though not complete, that calculate the time intervals between key positions or specific finger movements. Kinkead (1975) and Hirago *et al.* (1980) and Heath and Willcox (1990) are the most important studies in this area. Taking only the time intervals as the distance matrix can be used if your only objective is typing faster.

2.7.4. Keyboard Assignment Problem (KAP)

Besides linear and quadratic assignment formulations, a more general name which is called Keyboard Assignment Problem (KAP) is used for keyboard layout optimization. KAP describes all multi objective assignment formulations for keyboard layout development. The purpose of a KAP, which allocates M characters to N keys is to find a keyboard arrangement that optimizes a set of specified objectives. So KAP is the general name of keyboard assignment problems which includes multi objectives (Yin and Su, 2011). These objectives are: (i) typing a text without fatigue, (ii) maximizing typing speed, (iii) reducing the number of typing errors and (iv) allowing rapid mastery of the touch typing. However, these objectives cannot be easily translated into mathematical criteria which could serve for an evaluation of a given keyboard and also quantification of these criteria is not easy. As a matter of fact, ergonomic research in the field of computer keyboards has so far not been able to supply a satisfying set of rules for the ergonomic evaluation of a keyboard arrangement. The only rules one can hope for, therefore, consist of a collection of heuristic rules (Eggers *et al.*, 2003).

Marsan (as cited in Eggers et al, 2003) determined a number of criteria that can be used in evaluating a keyboard layout. These criteria as listed below are very similar to the criteria that are defined by Dvorak *et al.* (1936). (see Section 6.6).

- Accessibility and Load: The combination character sets should be distributed on the keys in a way that the total load is shared adequately by all fingers; and the fact that some keys are less accessible (difficult to reach) than others has to be taken into account.
- Hand alternation: The fastest and most comfortable typing is assured when consecutive keys are not hit by the same hand. This way while one hand is pressing a key, the other hand can prepare for the consecutive one.
- Consecutive usage of the same finger: Two consecutive keys should not be hit by the same finger. This is because of the preparation time for the next move as explained in Section 2.4. There is no preparation time if the digraph is pressed with the same finger.
- Avoiding big steps: When one hand is used for two consecutive hits, great distances

which require awkward hand postures should be avoided.

- Hit direction: For digraphs typed by one hand only, the preferred hit direction is from the little finger towards the thumb.

In our mathematical model which is in Section 4.2, monograph criterion is related with the first ergonomics criteria (accessibility and load) while the digraph criterion is related with all the others except hit direction.

The first criterion is related with monographs while others are related with digraphs. However, quantification of these criteria is again not easy. Eggers *et al.* (2003) tried to quantify these criteria by asking subjective opinions of two ergonomists. Although their methodology is evolutionary and is used by several other authors (Deshwal and Deb, 2006; Yin and Su, 2011), it is obvious that scientific studies are needed to quantify these criteria.

2.7.4.1. Solution Methods of Keyboard Assignment Problem. (a) *Exact algorithms*: They do guarantee the global optimum solution of keyboard assignment problems. Unfortunately, these methods generally try all combinations in the solution set. Hence, they need a great amount of time, sometimes even years. So metaheuristics are better in solving such problems.

(b) *Metaheuristics*: They are generally applied to problems for which there is no satisfactory problem-specific algorithm; or when it is not practical to implement such a method. Most commonly used metaheuristics target combinatorial optimization problems. However they can handle any problem that can be reformed in that form. There have been several metaheuristics previously that were used to find a near optimum solution of KAP. Below is a list of these metaheuristics:

- Genetic Algorithm (Malas *et al.*, 2008; Deshwal and Deb, 2006)
- Simulated Annealing (Light and Anderson, 1993)
- Ant Colony Optimization (Eggers *et al.*, 2003)
- Cyber Swarm Optimization (Yin and Su, 2011)

In addition, there are other metaheuristics such as taboo search, variable neighborhood search, local search, greedy randomized adaptive search procedure (GRASP), scatter search and bee colony optimization that can be used in the solution of KAP.

2.7.5. Summary of Findings

Different techniques have been used for keyboard layout generation. Most of the older keyboard layouts were developed using some heuristic rules while newer studies used assignment formulations, multi objective functions and metaheuristic optimization algorithms. With the use of optimization techniques, keyboard layout generation is broken into a new ground. However, the development in the technique does not come along with using valid model parameters. So although good approaches for solving the keyboard assignment problem were developed, these approaches lack in the use of accurate parameter values for solving the models. Most of them relied on subjective opinions of a few experts in determining the values of the parameters.

The best approach for keyboard layout optimization seems to be keyboard assignment problem since heuristic approaches are far from obtaining a near optimal solution and single objective assignment formulations either linear or quadratic are not sufficient for taking into consideration of all rules. However, the objectives and the parameters that are used in the keyboard assignment problems should be as objective as possible and as easy as possible to be implemented. To optimize such a multi objective formulation, the only logical solution seems to be using metaheuristic algorithms since exact algorithms cannot find the optimum result because of the problem size and complexity.

3. RATIONALE AND OBJECTIVES OF THE STUDY

The rationale and the objectives of the current study are explained in this chapter in details in the light of previous literature review.

3.1. Rationale of the Study

Despite all technological advancement in today's world, the keyboard still is the main device for text entry in computers. However, due to the deficiencies in the existing and commonly used keyboard layouts, the text entry jobs induce performance, health and comfort issues as addressed in the previous sections. Due to this fact, a number of researchers have strived and continue to strive to develop optimal keyboard layouts for their national languages to overcome these deficiencies. However, as the literature indicates, the existing approaches lack in a number of ways that are summarized below:

- (i) Although some good mathematical models are formed to optimize the keyboard layouts, none of these studies used objective parameter values to quantify the ergonomics criteria (e.g.,; accessibility and load, hand alternation, consecutive usage of the same finger, avoiding big steps, hit direction as described in Section 2.6 and Section 2.7). Instead, these studies used subjectively determined values of ergonomics parameters.
- (ii) None of the studies used Pareto-based optimization techniques which shows most of the near optimal keyboard layouts at once. Instead, they used aggregating objective functions which were eventually solved as a model with single objective function.
- (iii) None of the studies which used optimization techniques carried out validation studies which would prove that their layouts were better than the existing layouts.
- (iv) The existing F keyboard layout for Turkish language is lacking in terms of ergonomics criteria and in consideration of the complete characteristics of Turkish language as indicated in Section 2.6. The Turkish F layout is designed only for writing faster according to the letter frequencies in the Turkish dictionaries of 1950's. The drawbacks with this layout can be listed as follows: (i) only design objective of this layout was fast typing (ergonomics criteria is not considered), (ii)

letter frequencies are calculated from the dictionary of TDK of 1950's, (iii) the words used in Turkish language changed over the past 50 years.

Therefore; it is a matter of efficiency, health and comfort issue to develop an optimal keyboard layout for any language as well as Turkish while considering ergonomics criteria to reduce typing induced health problems and improve typing performance and comfort among typists.

3.2. Objectives of the Study

Based on the rationale stated in the previous section, the main objectives of this study are as follows:

- (i) Developing a novel methodology for generating ergonomic and optimal keyboard layouts that can be used for various languages to reduce fatigue, improve typing performance and comfort for touch typists
- (ii) Quantifying the ergonomics criteria objectively that will be used in the optimization model
- (iii) Developing an optimal and ergonomic keyboard layout for touch typing for Turkish language using the developed methodology
- (iv) Comparing the developed Turkish keyboard layout with F and Q layouts.

4. METHODOLOGY

In this chapter, the methodology to accomplish the stated objectives is explained in details.

4.1. Overview

Until now, different methods have been used for keyboard layout generation. These methods which contain heuristic methods, linear and quadratic assignment formulations and multi objective keyboard assignment formulations are explained in Section 2.7. Here in this chapter, the proposed methodology is discussed. This proposed methodology contains a multi objective keyboard assignment formulation with two objective functions. The parameters of this mathematical model are estimated with experimental studies which are also explained in this chapter. Besides, proposed methodology suggests using Pareto dominance concept instead of aggregating functions.

4.2. Proposed Optimization Model for Developing an Optimal and Ergonomic Keyboard Layout

Below is the overall mathematical model that is used in the optimization procedure in Section 6.3. The model is a keyboard assignment problem which has two objectives. It is selected because there is more than one objective in our formulation. The objective function has two objectives that are explained in the following section while it has the constraints of a regular assignment problem like assigning every facility to a location and every location to a facility. Its objective function is new to the literature.

$$\min Keyboard Penalty = \left(\sum_{f \in FINGERS} \left| \left(OL_f - \sum_{i \in MONOGRAPHS, j \in \pi(f)} MF_i * x_{ij} \right) \right|, \sum_{i, k \in MONOGRAPHS, j, l \in KEYS} DF_{ik} * Cost_{jl} * x_{ij} * x_{kl} \right)$$

subject to

$$\sum_{j \in KEYS} x_{ij} = 1 \quad \forall i \in MONOGRAPHS$$

$$\sum_{i \in MONOGRAPHS} x_{ij} = 1 \quad \forall j \in KEYS$$

$$x_{ij} \text{ is binary} \quad \forall i \in MONOGRAPHS, j \in KEYS$$

Sets:

FINGERS: the set of 8 fingers that are used for typing letters in touch typing.

HANDS: the set that consists of left and right hand.

MONOGRAPHS: the set of all 32 monographs (e.g., a, b, c, ..., q, w, x).

KEYS: the set of all keyboard keys (see Figure 4.1.).

$\pi(f)$: the set of all keyboard keys that are pressed by finger f such that $\pi(1)=\{1, 2, 3\}$, $\pi(2)=\{4, 5, 6\}$, $\pi(3)=\{7, 8, 9\}$, $\pi(4)=\{10, 11, 12, 13, 14, 15\}$, $\pi(5)=\{16, 17, 18, 19, 20, 21\}$, $\pi(6)=\{22, 23, 24\}$, $\pi(7)=\{25, 26, 27\}$, $\pi(8)=\{28, 29, 30, 31, 32\}$ (see Figure 2.11 and Figure 4.1).

Parameters:

OL_f : the desired target load on the finger f .

MF_i : the monograph frequency of monograph i in the corresponding language.

DF_{ik} : the digraph frequency in the corresponding language between letters i and k .

$Cost_{jl}$: digraph penalty score of finger movement that presses keys j and l consecutively.

Decision Variable:

x_{ij} : the binary decision variable that assigns monograph i to key j ($x_{ij}=1$, if monograph i is assigned to key j ; 0, otherwise).

~	!	@	#	\$	%	^	&	*	(	)	{	}	←
1	2	3	4	5	6	7	8	9	0	[	]		Backspace
Tab	1	4	7	10	13	16	19	22	25	28	30	32	
Caps Lock	2	5	8	11	14	17	20	23	26	29	31	Enter	
Shift	3	6	9	12	15	18	21	24	27	.	Shift		
Ctrl	Win Key	Alt								Alt Gr	Win Key	Menu	Ctrl

Figure 4.1. Key positions on a conventional keyboard.

4.2.1. Objective Function

The most important aspect of KAP is its objective function. Besides, as already mentioned in Section 2.7, quantification of ergonomic criteria is not easy and the calculation of the objective function for the KAP requires a significant amount of time.

The proposed objective function is a multi objective function with two objectives (minimizing monograph and digraph penalties). For this multi objective function, Pareto based methods were used for evaluating the objective function value of different solutions. In Pareto based method, one solution is dominant to another solution if and only if it has a better objective value in all of the objectives. This method is explained in details in Section 4.3.

Let's first explain ergonomic criteria that were used in the current study and the proposed methodology to quantify these criteria to be used in the objective function.

4.2.1.1. Monograph Penalty (MP). A monograph is exactly one character that is pressed by one keystroke. In the current study only letters are considered as monographs such as 'a', 'b', etc.

To reduce fatigue and risk of musculoskeletal disorders of hand and fingers, characters should be distributed on the keys in such a way that the total load is shared adequately according to the capacities of the fingers. This criterion is related with the accessibility and load criteria that were explained in Section 2.7.4.

Strength and tapping rate are considered two important parameters to determine finger capacities. Previous studies indicate that strength and tapping rate of the fingers decrease from the index finger to the little finger. For strength of the fingers, Haaland's study (1963) (see Table 2.4); and for tapping speed of the fingers Dvorak *et al.*'s study (1936) (see Table 2.5) can be seen.

Considering that typing tasks requires minimal finger pushing strength, but a high tapping rate; it is decided to use tapping rate as the critical variable to determine monograph penalties. However, the existing literature contains a few study (e.g., Riemer (1929) and Hoke (1922) as cited in Dvorak *et al.* (1936)) on tapping rate of all eight fingers and these studies has some limitations such as sample characteristics (e.g., age range), sample size and experimental setup (e.g., typewriter is used). Therefore, it is decided to conduct a new comprehensive tapping rate study to determine monograph penalties more accurately. The details of these experiments are given in Section 4.5.

The score evaluates the variance of the load distribution on the fingers from the ideal distribution on fingers and is given by the following equation;

$$MP = \sum_{f \in FINGERS} \left| \left(OL_f - \sum_{i \in MONOGRAPHS, j \in \pi(f)} MF_i * x_{ij} \right) \right|$$

FINGERS: the set of 8 fingers that are used for typing letters in touch typing.

MONOGRAPHS: the set of all monographs (e.g., 32 monographs used for Turkish language (a, b, c, ..., q, ..., w, x, y, z)).

$\pi(f)$: the set of all keyboard keys that are pressed by finger f according to touch typing such that $\pi(1)=\{1, 2, 3\}$, $\pi(2)=\{4, 5, 6\}$, $\pi(3)=\{7, 8, 9\}$, $\pi(4)=\{10, 11, 12, 13, 14, 15\}$, $\pi(5)=\{16, 17, 18, 19, 20, 21\}$, $\pi(6)=\{22, 23, 24\}$, $\pi(7)=\{25, 26, 27\}$, $\pi(8)=\{28, 29, 30, 31, 32\}$ (see Figure 2.11 and Figure 4.1).

OL_f : the desired target (ideal) load on the finger f calculated based on the finger tapping rates (see Section 4.5, Section 5.1, Table 5.10).

MF_i : the monograph frequency of monograph i in the corresponding language that is obtained from national corpus of the country (e.g., for Turkish language, see

Section 6.3).

x_{ij} : the binary decision variable that assigns monograph i to key j .

4.2.1.2. Digraph Penalty (DP). A digraph consists of two characters (letters) that are pressed after each other such as ‘af’. This penalty score is used for satisfying the ergonomics criteria other than accessibility and load, and hit direction (see Section 2.7). These ergonomics criteria are hand alternation, consecutive usage of the same finger and avoiding big steps.

Digraph penalties are used for determining how much effort is needed to press one key after another. For instance, pressing key 9 after key 7 is slower and needs much more effort than pressing key 11 after key 20 (see Figure 4.1). Because; in the digraph 7-9, the same finger (left middle finger) presses key 7 and then presses key 9. However, in digraph 11-20, there is alternating hand presses. Key 20 is pressed by right index finger and then key 11 is pressed by left index finger. As already explained in the previous sections, it is a known fact that alternating hand movement is fast while using the same finger in a digraph is slow. Also different fingers have different tapping speeds. There are several factors like these as already explained in the previous sections.

Instead of using many hard to quantify ergonomic criteria such as Dvorak *et al.*’s (1936) and Marsan’s (1976) criteria and to eliminate double counting of penalties, we use a single digraph penalty function. This penalty function is quantified by considering important characteristics of touch typing such as hand alternation, consecutive usage of the same finger, avoiding big steps for the same hand and speed. In the statistical analysis of the digraph experiments (see Section 5.2), how these effects affect the digraph penalty can be seen.

In order to do that, experiments were conducted whose details can be found in Section 4.5. The experimental setup was done considering the touch typing principles that are already mentioned in Section 2.4.

Experiments were conducted instead of evaluating the finger movements (typing digraphs) because of the difficulty of doing so as the number of degrees of freedom is

large, and multiple solutions are possible (Saltzman, 1979). Eight fingers each have three joints, with each bone controlled in its up and down motion (extension and flexion) by two tendons, and each tendon controlled by muscles located in the forearm.

The penalty score shows the total penalty that is incurred by the consecutive finger movements and is given by the following equation:

$$DP = \sum_{i,k \in MONOGRAPHS, j,l \in KEYS} DF_{ik} * Cost_{jl} * x_{ij} * x_{kl}$$

KEYS: the set of all keyboard keys.

DF_{ik} : the digraph frequency in the considered language between letters i and k .

$Cost_{jl}$: ergonomic cost of finger movement (digraph penalty score of digraph) that presses keys j and l consecutively. These are calculated from the digraph experiments (see Section 4.6 and 5.2).

Frequency matrix can be calculated using the national corpus of the considered country or from other sources (e.g., for Turkish language, Turkish National Corpus (Aksan *et al.*, 2012) is used for the calculation of the frequency matrix of the digraphs). Cost matrix is the ergonomic cost of moving from one letter to another and it is defined as the time lag for pressing one letter after another. For instance, the cost of digraph_{11,15} is the time that passes between the pressing key 11 and key 15 after each other and these costs are defined from the experimental studies in Section 4.6.

4.3. Determining the Solution Method of the Proposed Optimization Model

As explained in Section 4.2, proposed model has a multi-objective objective function with two objectives: minimizing the monograph penalties and minimizing the digraph penalties. The rest of the model (constraints) is the same as a standard assignment model with standard assignment constraints (see Section 4.2).

4.3.1. Complexity of the Model

If we just consider our digraph objective, then the model is reduced to a quadratic assignment problem (QAP) which is explained in Section 2.7.3.2. However, QAP is NP-hard and is still among the most difficult combinatorial optimization problems today. Solving general problems of size greater than 30 is still computationally impractical. And the proposed model has a size of 32 characters for Turkish language.

Nevertheless, the theoretical complexity is not sufficient to explain why it is so difficult to solve QAP to optimality, as very large instances of a great number of NP-hard problems can be solved exactly. The homogeneity of the values of the solutions, due to the structure of the problem, is a better explanation which means that we have a lot of solutions whose value is close to the optimum. And the lack of algorithms that find sharp lower bounds for QAP is another problem regarding with this issue. So, even when the best solution is obtained, it is very hard to prove its optimality. So nearly 75% of the authors working in this area used metaheuristics methods for the solution of QAP (Loiola *et al.*, 2006). For more details about the algorithms and complexity of the QAP, one can see the review by Loiola *et al.* (2006).

If we just consider the monograph objective, then the proposed model is reduced to a much simpler model that can be linearized and solved to the optimality. To linearize that model, only absolute value terms should be converted with an appropriate conversion.

So even with only one of the objectives (digraph objective) of the proposed model, it becomes an NP-hard problem. And with a size of 32 keys and locations, it is practically impossible to solve it to optimality. So as most of the authors do, for this study it is proposed to use a metaheuristic algorithm.

Among the metaheuristic methods since there are two objective functions in the proposed model and for using the Pareto dominance approach, it is decided to use a multi-objective evolutionary algorithm.

4.3.2. Multi-objective Evolutionary Algorithms

A multi-objective optimization problem (MOP) differs from a single-objective optimization problem because it contains several objectives that require optimization. When optimizing a single objective problem, the best single design solution is the goal. But for multi objective problems, with several and possibly conflicting objectives, there is usually no single optimal solution. Therefore, the decision maker is required to select a solution from a finite set by making trade-offs. A suitable solution should provide for acceptable performance over all objectives.

The main motivation for using evolutionary algorithms (EA) to solve multi-objective optimization problems is because EAs deal simultaneously with a set of possible solutions (the so-called population) which allows us to find several members of the Pareto optimal set in a single run of the algorithm, instead of having to perform a series of separate runs as in the case of the traditional mathematical programming techniques. Additionally, EAs are less susceptible to the shape or continuity of the Pareto front (e.g., they can easily deal with discontinuous and concave Pareto fronts), whereas these two issues are known problems with mathematical programming technique (Coello and Lamont, 2004).

4.3.2.1. Basic Concepts. In multi objective evolutionary algorithms (MOEA), there are some concepts that need to be clarified before moving on.

Global Minimum: Given a function f , the value f^* is called a global minimum of function f if and only if the value of f^* is less than or equal to the value of every other solutions in the feasible region.

Although single-objective optimization problems may have a unique optimal solution, multi objective problems present a possibly uncountable set of solutions, which when evaluated, produce vectors whose components represent trade-offs in objective space. A decision maker then implicitly chooses an acceptable solution (or solutions) by selecting one or more of these vectors.

Pareto Dominance: A solution u is said to dominate v (denoted by $u \leq v$) if and only if u has an objective function value less than or equal to v in every objective.

Pareto Optimality: A solution x is said to be Pareto optimal if and only if there is no solution x' in the feasible region for which x' dominates x .

So a Pareto optimal solution is a solution that is not dominated by other solutions. This means that there is no solution that is better than a Pareto optimal solution in every objective. These solutions are also known as non-inferior, admissible, or efficient solutions.

Pareto Optimal Set: Pareto optimal set of a multi objective problem is the set that contains all of the Pareto optimal solutions.

Pareto Front: Pareto front of a multi objective problem is formed by the objective function values of the Pareto optimal solutions.

The corresponding vectors of Pareto optimal solutions are known as non-dominated. Selecting a vector from this vector set (the Pareto Front set) implicitly indicates acceptable Pareto optimal solutions (genotypes). These are the set of all solutions whose vectors are non-dominated; these solutions are classified based on their phenotypical expression. Their expression (the non-dominated vectors), when plotted in criterion (phenotype) space, is known as the Pareto front.

4.3.2.2. Basic Operations in a MOEA. The objective of a MOEA is to converge to the true Pareto front of a problem which normally consists of a diverse set of points. Multi objective problems can present an uncountable set of solutions, which when evaluated produce vectors whose components represent trade-offs in decision space. During MOEA execution, a "local" set of Pareto optimal solutions (with respect to the current MOEA generational population) is determined at each generation and termed $P_{\text{current}}(t)$, where t represents the generation number. Many MOEA implementations also use a secondary population, storing all or some Pareto optimal solutions found through the generations. This secondary population is termed $P_{\text{known}}(t)$, also annotated with t (representing

completion of t generations) to reflect possible changes in its membership during MOEA execution. $P_{\text{known}}(0)$ is defined as empty set and P_{known} alone as the final, overall set of Pareto optimal solutions returned by a MOEA. Of course, the true Pareto optimal solution set (termed P_{true}) is not explicitly known for multi objective problems of any difficulty. P_{true} is defined by the functions composing a multi objective problem; it is fixed and does not change. $P_{\text{current}}(t)$, P_{known} , and P_{true} are sets of MOEA genotypes where each set's phenotypes form a Pareto front. The associated Pareto front for each of these solution sets is called as $PF_{\text{current}}(t)$, PF_{known} , and PF_{true} (Coello and Lamont, 2004).

In a MOEA, there are two main issues that differs from a single objective evolutionary algorithm. These issues are:

- (i) The selection of individuals such that non-dominated solutions are preferred over those which are dominated.
- (ii) Maintaining the diversity in the population.

These issues should be considered in a MOEA (Coello and Lamont, 2004).

4.3.2.3. Types of Multi Objective Evolutionary Algorithms. We can classify MOEAs into three categories:

- (i) *Aggregating Functions:* Classical optimization methods which use aggregating functions suggest converting the multi-objective optimization problem to a single-objective optimization problem by assigning weights to objectives and emphasizing one particular Pareto-optimal solution at a time. When such a method is to be used for finding multiple solutions, it has to be applied many times, hopefully finding a different solution at each simulation run (Coello and Lamont, 2004).
- (ii) *Population-based Approaches:* In population-based approaches, subpopulations are formed in every generation, each concerning only one objective. Then these subpopulations shuffled together. However, these approaches have several problems from which the most serious is that its selection scheme is opposed to the concept of Pareto dominance (Coello and Lamont, 2004).

- (iii) *Pareto-based (Non-dominated sorting) Approaches*: MOEAs that use non-dominated sorting and sharing (Pareto-based) have been criticized mainly for their computational complexity, non-elitism approach; and the need for specifying a sharing parameter (Coello and Lamont, 2004).

Among these approaches, Pareto-based approach is chosen to solve our proposed optimization model. Because instead of one single solution, this approach gives a set of solutions that cannot be dominated by other solutions and it is possible to see all these solutions (Pareto front) and chose among them. Among the Pareto-based approaches, non-dominated sorting genetic algorithm II (NSGA II) (Deb *et al.*, 2002) is selected as the specific algorithm to solve the proposed model. Because NSGA II can cope with the three problems that are criticized in Pareto-based approaches and this algorithm is proven to deal with multi-objective problems efficiently and effectively. The details of the algorithm are in the following section.

4.3.3. Non-dominated Sorting Genetic Algorithm II (NSGA II)

NSGA II is a fast and elitist multi-objective genetic algorithm. It can handle the computational complexity, non-elitism approach and the need for specifying a sharing parameter problem. For the details of how the algorithm overcomes these problems, reader can refer to Deb *et al.* (2002). Below is a brief description of the algorithm which is taken from Deb *et al.* (2002).

4.3.3.1. Fast Non-dominated Sorting Approach. First, for each solution two entities are calculated: i) domination count n_p : the number of solutions which dominate the solution p , and ii) S_p : a set of solutions that the solution p dominates.

All solutions in the first non-dominated front will have their domination count as zero. Now, for each solution p with $n_p=0$, each member (q) of its set S_p is visited and its domination count is reduced by one. In doing so, if for any member q the domination count becomes zero, it is put in a separate list Q . These members belong to the second non-dominated front. Now, the above procedure is continued with each member of Q and third front is identified. This process continues until all fronts are identified (see Figure 4.2).

<u>fast-non-dominated-sort(P)</u>	
for each $p \in P$	
$S_p = \emptyset$	
$n_p = 0$	
for each $q \in P$	
if $(p \prec q)$ then	If p dominates q
$S_p = S_p \cup \{q\}$	Add q to the set of solutions dominated by p
else if $(q \prec p)$ then	
$n_p = n_p + 1$	Increment the domination counter of p
if $n_p = 0$ then	p belongs to the first front
$p_{\text{rank}} = 1$	
$\mathcal{F}_1 = \mathcal{F}_1 \cup \{p\}$	
$i = 1$	Initialize the front counter
while $\mathcal{F}_i \neq \emptyset$	
$Q = \emptyset$	Used to store the members of the next front
for each $p \in \mathcal{F}_i$	
for each $q \in S_p$	
$n_q = n_q - 1$	
if $n_q = 0$ then	q belongs to the next front
$q_{\text{rank}} = i + 1$	
$Q = Q \cup \{q\}$	
$i = i + 1$	
$\mathcal{F}_i = Q$	

Figure 4.2. Fast non-dominated sorting algorithm of population P in NSGA II (Deb *et al.*, 2002).

4.3.3.2. Diversity Preservation. It is mentioned earlier that, along with convergence to the Pareto-optimal set, it is also desired that an MOEA maintains a good spread of solutions in the obtained set of solutions.

In NSGA II, the sharing function approach is replaced with a crowded-comparison approach that eliminates the difficulties of defining a sharing parameter and complexity issues regarding the sharing function.

NSGA II does not require any user-defined parameter for maintaining diversity among population members. This algorithm instead uses a crowding-distance based comparison. Also, it has a better computational complexity.

The crowding-distance computation requires sorting the population according to each objective function value in ascending order of magnitude. Thereafter, for each objective function, the boundary solutions (solutions with smallest and largest function values) are assigned an infinite distance value. All other intermediate solutions are assigned a distance value equal to the absolute normalized difference in the function values of two adjacent solutions. This calculation is continued with other objective functions. The overall crowding-distance value is calculated as the sum of individual distance values corresponding to each objective. After all population members in the Pareto front are assigned a distance metric, two solutions can be compared for their extent of proximity with other solutions. A solution with a smaller value of this distance measure is more crowded than other solutions (see Figure 4.3).

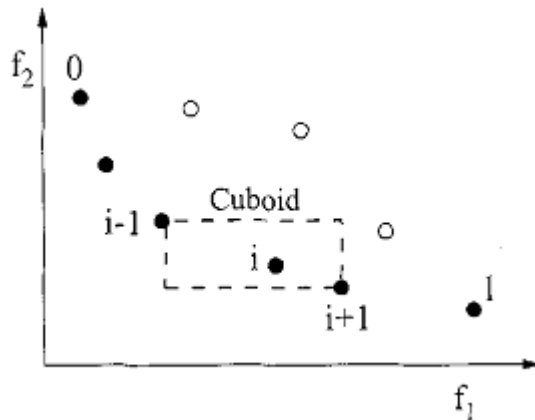


Figure 4.3. Crowding-distance calculation. Points marked in filled circles are solutions of the same non-dominated front.

So when in a tournament, to maintain the diversity as well as performance, crowded comparison operator is used. The crowded-comparison operator ($<_n$) guides the selection process at the various stages of the algorithm toward a uniformly spread-out Pareto optimal front. A solution $u <_n v$ in two cases 1) when its non-domination rank is smaller than v , 2) when its non-domination rank is equal to v and its crowding distance is greater than v .

That is, between two solutions with differing non-domination ranks, the solution with the lower (better) rank is preferred. Other-wise, if both solutions belong to the same front, then the solution that is located in a lesser crowded region is preferred (see Figure 4.4).

<u>crowding-distance-assignment($\mathcal{I}$)</u>	
$l = \mathcal{I} $	number of solutions in $\mathcal{I}$
for each i , set $\mathcal{I}[i]_{\text{distance}} = 0$	initialize distance
for each objective m	
$\mathcal{I} = \text{sort}(\mathcal{I}, m)$	sort using each objective value
$\mathcal{I}[1]_{\text{distance}} = \mathcal{I}[l]_{\text{distance}} = \infty$	so that boundary points are always selected
for $i = 2$ to $(l - 1)$	for all other points
$\mathcal{I}[i]_{\text{distance}} = \mathcal{I}[i]_{\text{distance}} + (\mathcal{I}[i + 1].m - \mathcal{I}[i - 1].m) / (f_m^{\max} - f_m^{\min})$	

Figure 4.4. Crowding distance assignment of solutions in NSGA II (Deb *et al.*, 2002).

4.3.3.3. Main Loop. The main loop of the algorithm is as follows:

Initially, a random parent population P_0 is created. The population is sorted based on the non-domination. Each solution is assigned a fitness (or rank) equal to its non-domination level (1 is the best level, 2 is the next-best level, and so on). At first, the usual binary tournament selection, recombination, and mutation operators are used to create an offspring population Q_0 of size N . Since elitism is introduced by comparing current population with previously found best non-dominated solutions, the procedure is different after the initial generation.

The t . generation of the algorithm is described here. A combined population $R_t = P_t + Q_t$ is formed. The population R_t is of size $2N$. Then, the population R_t is sorted according to non-domination. Since all previous and current population members are included in R_t , elitism is ensured. Now, solutions belonging to the best non-dominated set F_1 must be preferred more than any other solution in the combined population. If the size of F_1 is smaller than N , we definitely choose all members of the set for the new population. The remaining members of the population are chosen from subsequent non-dominated fronts in the order of their ranking. Thus, solutions from the set F_2 are chosen next, followed by solutions from the set F_3 , and so on. This procedure is continued until no more sets can be accommodated. Say that the set F_f is the last non-dominated set beyond which no other set can be accommodated. In general, the count of solutions in all sets from F_1 to F_f would be larger than the population size. To choose exactly N population members, we sort the solutions of the last front F_f using the crowded-comparison operator in descending order and choose the best solutions needed to fill all population slots. The NSGA-II procedure is also shown in Figure 4.5.

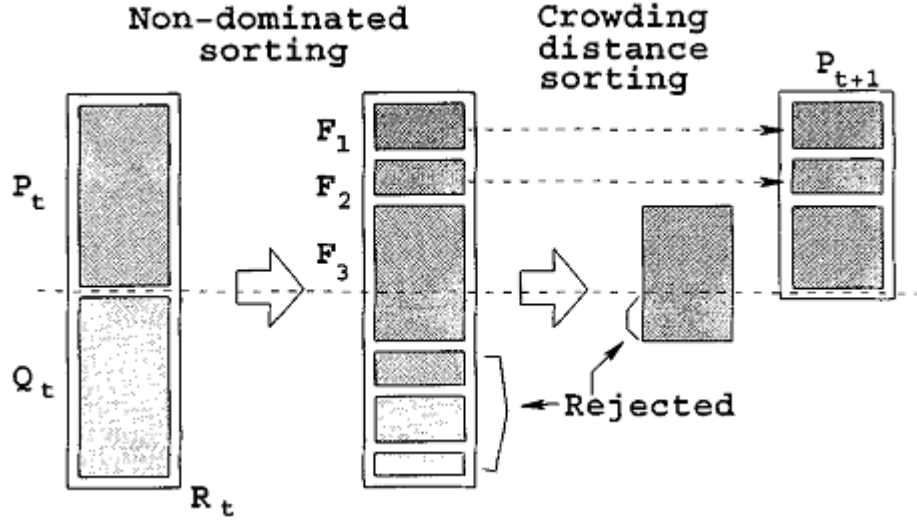
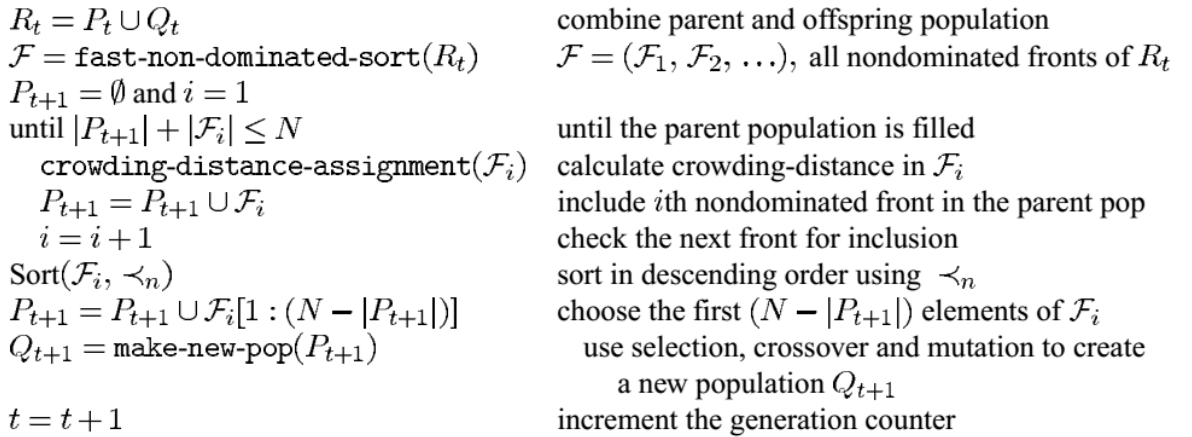


Figure 4.5. NSGA II procedure.

The new population of size N is now used for selection, crossover, and mutation (see Section 6.3 for crossover and mutation examples) to create a new population of size $2N$. It is important to note that we use a binary tournament selection operator but the selection criterion is now based on the crowded-comparison operator $\prec_n$. The diversity among non-dominated solutions is introduced by using the crowding comparison procedure, which is used in the tournament selection and during the population reduction phase (see Figure 4.6).

Figure 4.6. Main loop in NSGA II (Deb *et al.*, 2002).

4.4. Keyboard Used and Space Bar

The monograph and digraph penalties as described in Section 4.2 are determined based on keyboard experiments. These experiments are performed on conventional keyboards.

4.4.1. The Keyboard

As explained in Section 2.3, split keyboards are designed to straighten the wrist and to reduce ulnar deviation of the wrists. And it is the only keyboard design that has proven to be superior to conventional keyboard design. However, commercial split keyboards do not have exactly the same geometry that is proposed by ergonomists. And it is a common fact that a very high majority of the typists use conventional keyboards. So proposed layout generation procedure is applied to a conventional keyboard design (see Figure 2.1). Therefore all the experiments on digraph penalties as explained in Section 4.6 are performed using a conventional keyboard and are valid for conventional designs. In order to develop a keyboard layout for a split keyboard, all the digraph experiments must be repeated in the split keyboard design.

4.4.2. The Space Bar

The space bar seems as wasted opportunity since most of the skilled typists use only the right thumb to type spaces by using a small section of the bar which can easily accessible. So in the current study, initially it was decided to split the space bar into two. Right piece would serve as the space bar and left piece as the backspace. Space bar would be operated by right thumb while backspace would be operated by left thumb. Thus, the backspace which is one of the most often used and hardly accessed key would easily be accessible.

This is also in the same direction our cognition captures the movement which is backspacing is done with left thumb and moving forward with a space is done with right thumb. This property is also applied by Maltron keyboards (Hobday, 1995). Although it seems very logical, we do not have experimental data about this property since in the

experiments this new property is not tested. That is, the space bar was not split into two sections in the current study.

4.5. Experimental Study 1: Finger Tapping Rates

In this experimental study, finger tapping rates are calculated for 8 fingers for the purpose of determining the target (ideal) finger load of each finger for touch typing. These values together with the monograph frequencies of the corresponding language are used to determine monograph penalties as described in Section 4.2.1.1.

In this section of the methodology, this study is explained. The results of the study are explained in Section 5.1. The way how these calculated parameters are used in the optimization is explained in Section 4.2.1.1 and Section 6.3.6.

4.5.1. Rationale and Objectives of the Experiment

Finger tapping rate is the total number of finger taps in a specified period of time and it is commonly used as a psychomotor test for evaluating the patients who have neurologic problems like Parkinson, schizophrenia, Alzheimer, etc. (e.g., Dodrill and Troupin, 1979; Wing *et al.*, 1984; Ott *et al.*, 1995). Generally, it is measured as the number of taps of the index finger in 10 seconds (e.g., Schmidt *et al.*, 2000; Cousins *et al.*, 1997). It is used to evaluate the integrity of the neuromuscular system and examine motor control. It assesses simple motor control and manual dexterity.

In the field of ergonomics, the tapping rate capacity of fingers can be used as a design criterion in various products; for example, in the keyboard layout generation (e.g., Dvorak *et al.*, 1936; Eggers *et al.*, 2003; and Yin and Su, 2011), and in the designs of some musical devices (e.g., piano), tools and machines that require high rates of finger tapping. In the keyboard layout generation case, the mentioned studies distributed the number of key presses to the fingers according to some defined capacities of the fingers (see, OL_f parameter in the mathematical model in Section 4.2).

Finger tapping rate is affected by a number of factors. There are studies that attempted to identify these effects with some lacks. For instance, Cousins *et al.* (1997) studied the effects of age and found that older subjects performed fewer total finger taps than younger subjects. Schmidt *et al.* (2000) investigated the effects of gender and hand preference on index finger tapping rate and found that men performed faster and more regularly than women. They explained this phenomenon with the effects of male hormones (testosterone) on muscles. They also concluded that hand preference doesn't have a significant effect on overall tapping rate. However, in the same study they found that manual asymmetry (difference in tapping rate) between left and right hands are smaller in left-handed subjects. Silver *et al.* (2002) studied the effects of smoking on index finger tapping rate of schizophrenic patients and found that smoking is associated with faster central processing. Perkins *et al.* (1990), and Roth and Batting (1991) also found that nicotine administration can increase finger tapping rate in normal smokers. However, the mechanism by which nicotine improves central processing is unknown (Silver *et al.*, 2002).

There are very few studies about the tapping rate of different fingers since most of the literature is about the tapping rate of index fingers. One of these few studies was done by Jackson (1953) who worked on four fingers of the right hand and found that tapping rates of index and middle fingers are not significantly different. However, tapping rates for the ring and little fingers were significantly lower than for those two.

As the review of the literature shows, most of these studies are limited to the index finger of the right hand. Sample sizes of the studies in the literature generally vary between 50 and 100. There is no study that investigated the effects of age, gender, fingers, time duration, hand preference, smoking and exercise on tapping rate in a single study, considering a wide spectrum of age range.

Therefore, the objectives of this experiment were set as follows: determining tapping rate capacities of fingers (or, the desired target load on the fingers as stated in Section 4.2) to determine monograph penalty along with the monograph frequencies of the considered language; and determining the finger, gender, tapping duration, hand preference and age effects on the finger tapping rate.

4.5.2. Pilot and Repeatability Study

In order to define the necessary experimental procedure, pilot studies are done using 68 subjects who are selected from the university population. 75% of these subjects were males. In these pilot studies, the focus is on the tapping time and the experimental procedure. It is seen that after about 30 seconds tapping in the maximum voluntary tempo, the tapping time was getting steady (i.e., not changing significantly). Hence, it is decided to set the tapping duration as one minute in main tests for every finger. In addition to overcome fatigue, a 30 seconds rest period is provided between two consecutive trials using the feedback of subjects in these pilot studies. Experimental procedure and use of a laptop computer revealed no problems, so they are used in the main tests as explained in the next section.

In this pilot study, for the evaluation of subjective rating of fatigue after one minute tapping, a 5 level Likert scale was used. However, the scores obtained were too small meaning that the fatigue is very small. So in the main tests, it is decided to use a larger scale (10 points Borg's rating of perceived exertion scale (Borg, 1998)) to evaluate the small amount of subjective fatigue better.

A repeatability study is also done. 8 subjects repeated the same procedure in two different days and time of the day. The differences between two repetitions were lower than 10% in 92% of the time. Although there is no certain rule, up to 15% of difference between two repetitions is accepted in ergonomics science (e.g., Snook and Ciriello, 1991). Therefore, this repeatability power is acceptable for the current study.

4.5.3. Subjects

The sample of participants consisted of 71 male and 77 female adults (a total of 148) with a wide range of age spectrum (18 to 85 years). All subjects participated in this study were in good physical health, and had no records of upper extremity, neck or shoulder disorders or pain. A self-reported survey tool was used to determine the health status of the subjects. All of the subjects signed an informed consent form after a full explanation about the study procedures prior to experiments and experimental procedures

were approved by the Human Subjects Committee at Boğaziçi University.

Age range is divided by 10-year intervals. The number of subjects was distributed approximately evenly between gender and age groups. However, the proportion of the left handed subjects was not more than actual proportion which is about 7-10% of the total population. The distribution of participants by gender, age-group and hand preference can be seen in Table 4.1. Although there are left handed subjects in our data set, in our analysis, we did not consider them because of our decision of forming a keyboard layout just for right handed people. Also the data of subjects who are older than 70 were ignored since there are very few typists who work after 70. So the data of a total of 115 subjects (56 male and 59 female) aged between 18 and 70 are considered for developing the optimal keyboard layout.

Table 4.1. The distribution of the participants by gender, age-group and hand preference.

	Males		Females	
Age	Right handed	Left handed	Right handed	Left handed
18-29	12	1	13	1
30-39	9	2	10	1
40-49	11	1	11	1
50-59	13	0	13	2
60-69	11	0	12	0
70 and above	11	0	12	1
Total	67	4	71	6

4.5.4. Equipment and Set up

A notebook computer was used as the test device as shown in Figure 4.7. A computer program that is written in MatLab was installed into that computer, and during all experiments the same notebook computer was used. While subjects performed tapping with the specified finger at his/her maximum volitional speed, the same computer program counted and recorded the number of taps every five-seconds. (The MatLab code for the program can be found in Appendix A. However the screen print-outs are in Turkish since the subjects are from Turkish population).

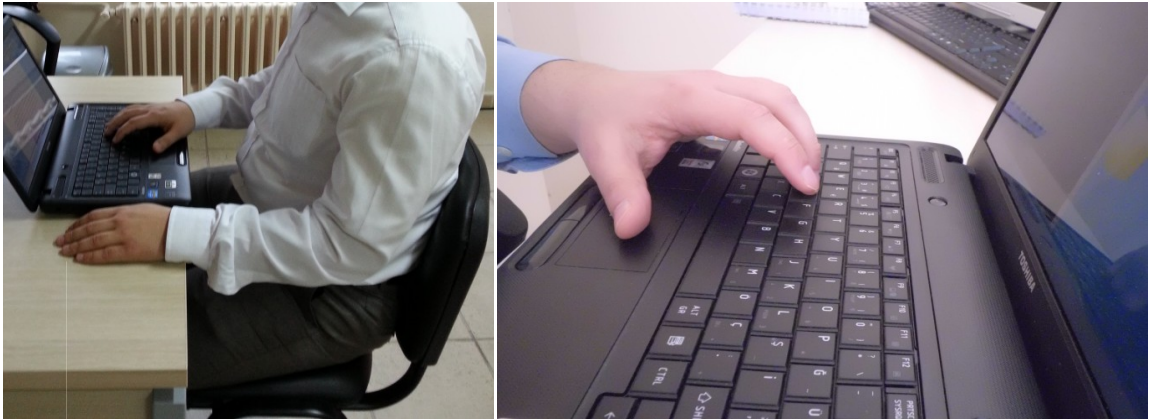


Figure 4.7. During the tapping tests, a notebook computer was used. The subject was seated in neutral sitting posture with keyboard at about elbow height while the thumb and bottom part of palm were supported.

4.5.5. Experimental Procedure

Prior to the experiments, some characteristics of the subjects such as gender, date of birth, dominant hand, daily cigarette usage, weekly exercise rate and occupation are recorded. In addition, several anthropometric variables (hand length and breadth, and middle finger length) were measured. The descriptive statistics of the participants can be found in Table 4.2.

Table 4.2. Descriptive statistics of participants.

	Male $\bar{x} \pm s$ (range)	Female $\bar{x} \pm s$ (range)
Age	48.7 ± 18.1 (18.0 - 80.8)	49.2 ± 18.6 (18.2 - 84.6)
Hand Length (mm)	184.7 ± 10.5 (158 - 203)	168.4 ± 11.5 (134 - 191)
Middle Finger Length (mm)	79.5 ± 4.5 (69 - 87)	72.6 ± 4.4 (63 - 82)
Hand Breadth (mm)	84.6 ± 5.6 (73 - 99)	74.9 ± 5.2 (65 - 88)
Smoking (packages / day)	0.25 ± 0.48 (0 - 2)	0.11 ± 0.30 (0 - 1)
Exercise (exercise / week)	1.17 ± 1.69 (0 - 7)	0.73 ± 1.30 (0 - 5)

A briefing was given to the subjects regarding the task and experimental procedure. A few trials were performed for the purpose of familiarization before the actual tests.

The experimental task consisted of tapping the specified key in the keyboard with the specified finger for a period of one minute with the maximum volitional tempo (as fast as possible). The subject was seated in neutral sitting posture with keyboard at about elbow height while the thumb and bottom part of palm were supported. The associated key was the standard position on the home row of the specified finger for touch typing (see Figure 2.10). For instance, for left little finger, subject typed on key A (on Q layout) repetitively with his/her maximum tempo for one minute. After one minute tapping for every finger, subjects are asked for their subjective rating about the fatigue in their associated finger according to 10 points Borg's rating of perceived exertion scale (Borg, 1998). This is done just for evaluating the subjective ratings for the fatigue for different fingers, however for the calculation of target finger loads, these ratings are not used.

One minute time is selected as the tapping time per finger since in the pilot studies after 30 seconds there was a steady rate of tapping. Experiments were carried out with all eight fingers except thumbs. The order of the eight fingers was randomized for each subject to reduce experimental error. Between the two test sessions, there was a 30-second rest time for recovering from the fatigue. In addition, to minimize fatigue effect, finger of one hand followed the finger of other hand: such as one left hand finger, then one right hand finger, then one left hand finger, and so on.

There was no feedback to the subject about his/her speed during the experiments but they are encouraged to perform tapping as fast as possible.

4.6. Experimental Study 2: Digraph Tapping Rates

In this experimental study, digraph tapping rates are calculated for all digraph combinations. These digraph tapping rates along with the digraph frequencies of the considered language are used to calculate digraph penalties as explained in Section 4.2. In this section, this experiment is explained. The results of the experiment are explained in Section 5.2 and the way how these calculated parameters used in the optimization is explained in Section 4.2 and Section 6.3.6.

4.6.1. Rationale and Objectives

In order to solve and optimize the mathematical model in Section 4.2 and find an optimal keyboard layout, first we need to quantify the digraph parameters in it. However, there is no scientific study to be used for quantifying the digraph penalties. All studies until now were based on subjective ratings of ergonomists. This experiment is on finger movements and therefore quantifies the digraph penalties related to each finger movement between digraphs.

By quantifying the digraph tapping rates in the model, we also define universal parameters that are true for all conventional keyboards. Therefore, one can use these in the languages other than Turkish by modifying only the frequency of monographs and digraphs for the considered languages.

To conclude, the objective of this experiment is quantifying the digraph penalty costs of each digraph by calculating its digraph tapping rate.

4.6.2. Pilot and Repeatability Study

In order to define the necessary experimental procedure, pilot study was done using four subjects. In this pilot study, the aim was finding the most appropriate way for differentiating digraph penalty scores from each other. The method should have distinguished the penalty scores from each other with a good metric and also it should have been reliable, so repeatable. In order to find a method like that different techniques were tested during this pilot study.

Firstly, it was tried to use the force measurement technique for evaluating the fatigue of each digraph as a means of digraph penalty scores. In this technique, two maximal finger pushing force measurements were taken from the subjects just before and after the experiments and percent decrease in the maximal finger pushing force was noted. During this experiment, subjects repetitively typed a given digraph with the same tempo using a metronome for different periods of time. Different tempo levels are tested. In lower tempo (less than 200 beats per minute (bpm)), the force reduction was not significant, not more

than 5%. In high tempo more than 230 bpm, subjects could not cope with the tempo. In medium tempo (between 200 and 230), there was a significant decrease in the maximal forces between 7% and 12% after two minutes tapping. However, when the experiments were repeated, these results (not the percentage difference between the repetitions) changed more than 5% meaning that the percentage difference between the repetitions was about 60%. So this technique seemed not reliable enough to differentiate the penalties with accuracy.

Secondly, it is tried to use the EMG signals that were taken from FDS muscle during the experiments. Again a fixed tempo was used. Since subjects could not cope with a tempo higher than 230 bpm, 230 bpm is selected for the maximum achievable tempo level in order to detect the fatigue in the muscle faster. Different test durations as long as 5 minutes were tried. However, when the median frequency of the EMG signal was analyzed, it was seen that there was not a significant decrease to detect the muscle fatigue. Also the results do not seem to differentiate the penalties from each other since the median frequency drop were very close to each other for different types of digraphs.

So as a last option, it is decided to use the typing speed of the subjects for different digraphs. In this technique, the tempo was not fixed, instead during the experiments subjects typed with their maximal voluntary speed (as fast as possible). Different time intervals were used for this experiment and was seen that after a certain amount of time, typing speed for all the digraphs began to be similar. However, in shorter periods they differ from each other in a good manner. So two minutes is taken as the time period and the same experiments were repeated. It was also seen that the difference between repetitions were small which stated that this technique was repeatable. So it is decided to use this technique which is explained in details below. It is also decided to take EMG signals from FDS muscle during these experiments for possible use.

4.6.3. Subjects

Eight participants (4 male and 4 female) were recruited from the university population. Participants ranged in age from 19 to 28. All subjects, participating in this study, were in good physical health, and have no records of upper extremity, neck or

shoulder disorders or pain. Except one of the female participant, all other participants were right handed and all used computers at least ten times per week for a total of at least 8 h per week.

All of the subjects signed an informed consent form after a full explanation about the study procedures and experimental procedures were approved by the Human Subjects Committee at Boğaziçi University.

The subjects' height and weight without shoes were measured. Also hand and palm lengths, hand breadth and all finger lengths were measured for both hands using a caliper. Hand and wrist circumference were also measured for both hands using a measuring tape. For baseline and descriptive purposes, single finger tapping rates of 8 fingers (excluding thumbs) were measured for 15 seconds. During these 15 seconds, subjects repetitively typed the associated key of the finger on the home row; i.e., key 11 for left index, key 29 for right little fingers (for key numbers, see Figure 4.1) and tapping rate of every finger is calculated. Overall tapping rate and error rate of the subjects during all experiments are also calculated. These tapping rate data is not used for further analysis. All these characteristics of the subjects are summarized in Table 4.3.

Table 4.3. Characteristics of the subjects for digraph tapping rate experiment

	Subject 1		Subject 2		Subject 3		Subject 4		Subject 5		Subject 6		Subject 7		Subject 8	
Gender	Male		Male		Female		Female		Male		Male		Female		Female	
Stature (mm)	1820		1802		1643		1568		1690		1830		1570		1700	
Body mass (kg)	89		58		54		83		83		83		57		56	
BMI (kg/m ²)	26.9		17.9		20.0		33.8		29.1		24.8		23.1		19.4	
Error rate	2.73%		0.77%		3.35%		4.31%		1.90%		1.39%		1.33%		3.55%	
Overall tapping rate (taps/sec)	5.45		6.02		5.01		6.51		5.67		5.59		4.48		4.82	
	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left
Index finger tapping rate	95	87	92	84	76	81	100	82	93	84	86	77	91	87	104	86
Middle finger tapping rate	93	89	87	86	78	86	88	80	92	79	91	78	93	86	102	85
Ring finger tapping rate	85	81	107	80	71	75	85	78	95	79	94	78	97	85	101	84
Little finger tapping rate	77	72	94	77	65	66	82	69	89	75	92	75	88	83	93	83
Hand length	190	193	191	193	183	174	159	162	186	182	194	193	167	165	174	171
Hand breadth at knuckles	84	86	84	85	73	70	78	75	80	80	85	83	72	73	73	72
Palm length	110	110	106	109	103	100	87	89	106	109	109	110	95	95	94	96
Circumference at knuckles	195	204	203	206	143	145	176	180	208	203	208	213	176	175	185	170
Wrist circumference	175	175	158	161	166	160	188	180	182	175	179	186	156	150	146	152
Index finger tip to crotch length	72	72	77	76	67	67	66	65	73	73	77	77	64	66	70	68
Middle finger tip to crotch length	79	80	83	83	75	72	68	67	76	76	84	82	69	71	73	72
Ring finger tip to crotch length	76	78	78	78	66	67	60	63	72	71	78	77	64	64	67	66
Little finger tip to crotch length	65	65	68	68	57	55	50	50	63	60	64	62	51	54	54	55
Thumb tip to crotch length	63	64	58	64	61	61	56	56	66	65	69	69	60	60	60	56

Notes: all tapping rates except overall tapping rate are measured for 15 seconds, all anthropometric measurements are in mm except body mass which is in kg and BMI which is in kg/m², and error rate is the overall error rate in the experiments per hundred characters.

4.6.4. Equipment and Set up

In the laboratory, a workstation that typists used in daily working was built. In this workstation, each subject performed the task on a windows-based personal computer placed on an adjustable workstation, while seated in a fully adjustable chair. The height of the tabletop was 75 cm. The monitor was adjusted so that the top line of the monitor was at the same level with the horizon from the eyes and approximately 60 cm from the eyes. The temperature is kept constant at 24° C during the experiments using an air conditioner.

To allow maximum personal comfort and standardize the postures, subjects were instructed about ANSI/HFES 100-2007 standard “Human Factors Engineering of Computer Workstations”. Among the three reference sitting postures (recline, upright and decline), upright sitting posture is adapted. In this posture, the user’s torso and neck are approximately vertical and in line (between 90° and 105° to the horizontal). The thighs are approximately horizontal and lower legs are vertical. For the remaining specifications, see Table 4.4. Then all subjects were asked to adjust the height of the seat and the backrest inclination based on personal preference, and then it was checked and made sure that postural angles of the subjects while typing were within the range listed in Table 4.4. The values in Table 4.4 are adopted from ANSI/HFES 100-2007.

Table 4.4. Requirements of postural angles during typing experiment (adapted from ANSI/HFES 100-2007).

Postural Element	Angle (degrees)
Torso and neck inclination	90-105
Torso to thigh angle	≈90
Knee angle	≈90
Elbow flexion	70-135
Shoulder abduction angle	<20
Shoulder flexion angle	<25
Wrist flexion angle	<30
Wrist extension angle	<30

The keyboard used in the experiments was a standard keyboard with conventional geometry (Figure 2.1). For supporting the forearm, approximately 15 cm space is provided

between the end of the wrist support and the table edge. The keyboard configuration angles and dimensions are listed in Table 4.5.

Table 4.5. Characteristics of the keyboard used in the experiments.

Lateral angle	0°
Split angle	0°
Slope (positive)	18°
Height ^a	27 mm
Distance between two adjacent keys on the same row ^b	19 mm

^aHeight measured from the surface top to the top center of the keys on the home row

^bDistance is measured between the centers of the keys

4.6.4.1. Electromyography (EMG). Median frequency of the EMG signals is used for quantifications of fatigue. So, in order to quantify the fatigue for all the digraph, during the experiments electromyography data is also collected from the subjects. Single differential surface electrodes (Delsys® DE-2.1) were used in this study. These electrodes had a parallel bar geometry with each of the bars was one cm long and the spacing between bars was one cm. Surface electrodes were placed on the skin of both forearms to record the muscle activities of the underlying finger flexor muscle (flexor digitorum superficialis (FDS)). The reference electrode was attached on the subject's olecranon of the same arm. The placement of the electrodes was chosen based on the technical notes from the manufacturer (Delsys, 2011). The final positions of electrodes were over the palmar side of the forearm and approximately located at the muscle belly by applying the electrode placement recommendations of the manufacturer (See Figure 4.8).

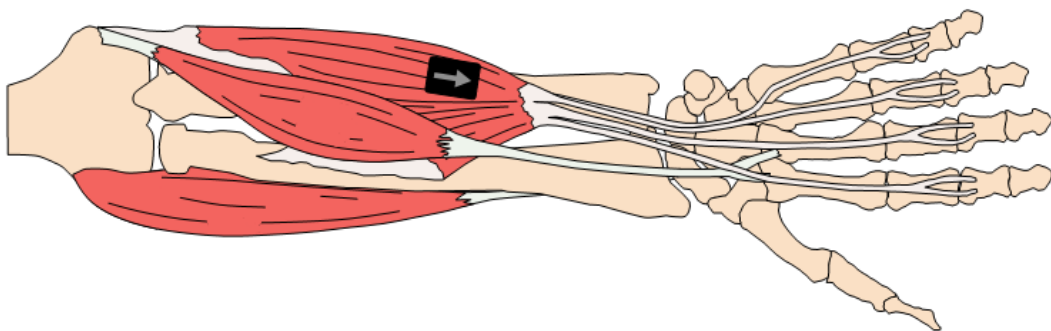


Figure 4.8. Placement of the electrode on the flexor digitorum superficialis muscle.

At the start of each day, subjects performed a normalization study to be able to normalize all EMG signals within that day. During these normalization studies, EMG data is collected while the subjects were resting their forearm and while they were squeezing a hand dynamometer with maximum voluntary isometric force. Then from these data, rest and maximum RMS values were calculated.

The raw EMG data at a sampling rate of 1000 Hz were filtered with two filters: a band pass filter in the range of 20-450 Hz and a band stop filter between 49 and 51 Hz to eliminate the noises in the signal. The band pass filter was the recommendation of the manufacturer while the band filter was put to eliminate the noises from electrical devices whose frequency are 50 Hz in Turkey.

From the filtered EMG data; RMS EMG values are calculated and these values were normalized using the associated day's rest and maximum RMS values.

Using the EMGworks software, median frequency of the EMG signals were also calculated and evaluated for fatigue analysis.

4.6.5. Experimental Procedure

This was an experimental laboratory study in which complete randomized block design (subjects as block) was used. In the experiment, each of the eight subjects performed 241 two minute typing task on a conventional keyboard. 105 of these 241 typing tasks were left hand key combinations and 136 of these 241 typing tasks were right hand key combinations. Left hand key combinations are the binary combinations of keys from key 1 to key 15 for which left hand is responsible in touch typing; and right hand key combinations are the binary combinations of keys from key 16 to key 32 for which right hand is responsible in touch typing (see Figure 4.1). Because of the setup of the experiment, it is not possible to detect the differences of the hit direction. So digraph_{i,j} and digraph_{j,i} is treated as the same digraph in all the experiments and analysis. No two hand digraph tapping rate was measured because the experimental setup was not appropriate for that.

For each of these two minute experiments, subjects were asked to type as fast as they could on the selected key combination. Two minutes is selected as the tapping duration, since as explained in the pilot study after some time the tapping rate becomes steady and similar for all the digraphs. So two minute was a long period enough to differentiate the digraphs while avoiding of steady and similar tapping rates. This experiment was done using the touch typing principles which means that the keys in the combination were pressed with the associated fingers in touch typing. For instance; in key combination between key 23 and key 31, subject performed a typing for two minutes in his/her maximum voluntary speed while his/her right middle finger was pressing key 23 and right little finger was pressing key 31 consecutively (key23, key31, key23, key31, ...).

In the experiments, subjects typed using a special program written in Java. This program divided two minutes into 4 thirty second periods and calculated the number of correct taps and errors per every period. Dependent variables in the experiment were the total number of characters typed and the number of errors in each 30 seconds period. The independent variables during the statistical analysis are explained in Section 5.2.

Trials were done in groups of 9 combinations. All 241 digraph combinations were randomized such that within each group, subjects performed 5 right hand and 4 left hand key combinations. These combinations were performed in such a way that left hand combinations were always preceded by right hand combinations. This way subjects could rest their hands at least 10 minutes between two combinations of the same hand. In addition to that, between each group subjects were allowed to rest at least 15 minutes. In each day, at most 4 groups of trials ($9 \times 4 = 36$ combinations) were performed in order to avoid overall fatigue of upper extremities and whole body.

For each subject, total time for the experiments except the resting times was about 8 hours. However, because of not having overall fatigue, every subject spent approximately 7 workdays while working about 4 hours every day. So it took about 60 workdays to complete this experiment.

4.7. Limitations of the Methodology

As every methodology, this methodology has some limitations that are originated from the assumptions, scope and subject characteristics. Although these limitations are explained through the text, they are also summarized as a list below:

- The parameters used to estimate the digraph penalties are based on the experiments performed using a conventional keyboard. Although this seems like a limitation, we strongly believe that the methodology proposed by this study is applicable to alternative keyboard geometry such as split keyboard.
- The digraph experiment was performed using the touch typing principles. Hence, the optimization results and proposed layouts may be valid for the touch typists. If typist does not type according to the touch typing principles, then the proposed keyboard layouts may not have the same effect on the typing speed and ergonomics of typing. To design a keyboard layout for a different typing method; for instance, two or eight finger typing, all of the digraph experiment should be repeated according to the principles of the corresponding typing method.
- The proposed methodology can be used in any language which has less than or equal to 32 letters. If the considered language has more than 32 letters, then mathematical formulations and the optimization procedure should be changed to allow assigning more than one letters to each key.
- In the digraph experiment, subjects were between 19 and 28 years old. Older people were not tested. So if there is an interaction effect between the tapping speed in the digraph experiments and the age, the digraph parameters do not include that effect. For instance, in our experiments the digraphs of the little fingers were slower than the other, if older people would have a higher tapping rate for their little finger than their ring fingers, then there would be an interaction effect between the digraphs and the age. However, if all the tapping rates decrease with the same rate when people gets older, then this means there is no interaction effect between the digraphs and the age. Note: In the monograph experiments, subjects were between 18 and 85 years old, however no significant interaction effect is found between the tapping rate and the age group.

- In the digraph experiment, because of the experimental setup and procedure it was impossible to consider hit direction. Hence, it was assumed, for instance, pressing key 7 after key 12 has the same digraph tapping rate as pressing key 12 after key 7. However as explained in the text, hit direction can have an effect on tapping rate. Pressing from little finger towards index finger (outside-in) is better than pressing from index finger towards little finger (inside-out).
- For the digraph tapping rates of digraphs that are tapped with different hands, no experiments are done. Because, the current experimental procedure and setup is not sufficient to calculate the digraph penalties of digraphs which are pressed by different hands. Instead, these digraph penalties are estimated using the experimental results of digraphs for the same hand. So as explained in Section 5.2, some assumptions should have been made.

5. EXPERIMENTAL RESULTS

In this chapter, the results for the monograph and digraph experiments are discussed. Besides, calculations of the monograph and digraph penalty scores from the experimental results are also explained here.

5.1. Results of Experimental Study I and Calculation of Monograph Penalties

Experimental results for the monograph experiment as well as how these results are converted to monograph penalties are explained in this section.

Although there were 10 left handed subjects and 24 subjects who are above 70 in our sample, in the following analysis the data from these subjects were discarded and only the data from right handed people whose ages are less than 70 were considered. This is because of the decision of forming a keyboard layout just for right handed people. Also the data of subjects who are older than 70 were ignored since there are very few typists who work after 70.

5.1.1. Factor Effects

Our main aim in the monograph experiment is calculating the tapping rate capacities of fingers (the desired target loads on fingers). However, as the data is collected from a wide range of subjects who have different characteristics, some statistical analysis can be done on the effects of factors that affect tapping rate. So before proceeding with calculation of the tapping rate capacities of fingers, these factor effects are analyzed in this section.

5.1.1.1. Response Variable and Investigated Independent Variables. The number of keystrokes in every 5-second period of 60 seconds is used as the dependent variable. That is, each of 1-minute experiments is divided into 5-second periods (a total of 12 periods in 60 s) to investigate the changes in the response from first period to the last period. The independent variables are age group (5 levels), gender (2 levels), finger (8 levels), period

(12 levels), smoking (2 levels) and exercise (2 levels). All the factors are categorized. Smoking is defined as smokers and non-smokers. Subjects who had never smoked before or subjects who has quit smoking at least one year ago are categorized as non-smokers while all the others are categorized as smokers. Subjects who has been doing regular body exercises are categorized as exercising and others as not exercising. Most of the subjects in the sample were non smoker and not exercising subjects (see Table 5.1).

Table 5.1. Dependent and independent variables and their levels used in the statistical analysis

	Name	Levels
Dependent variable	Number of keystrokes per 5 seconds	
Independent variables	Age	18-29, 30-39, 40-49, 50-59, 60-69
	Gender	Female, Male
	Fingers	Left little, Left ring, Left middle, Left index, Right index, Right middle, Right ring, Right little
	Periods	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
	Smoking	Smoker, Non smoker
	Exercise	Exercising, Not exercising

5.1.1.2. Descriptive Statistics of Response Variable. The collected tapping rate data are summarized by box plots (Figures 5.1-5.4) and a table (Table 5.2). The box plots depict mean (circles), median, 1st and 3rd quartile and range values and spread of the data, and Table 5.2 depicts the mean, standard deviation and range values of the tapping rate (number of taps / 5 seconds) data stratified by gender, age and finger combinations. In Table 5.2, for example, mean value of tapping rate is the average of 12 tapping rates corresponding to the 12 five second periods. In this table, it can be seen that average tapping rates for each finger generally decreases with the increasing age; and again average tapping rates generally decreases moving from index finger to little finger and from right hand to left hand.

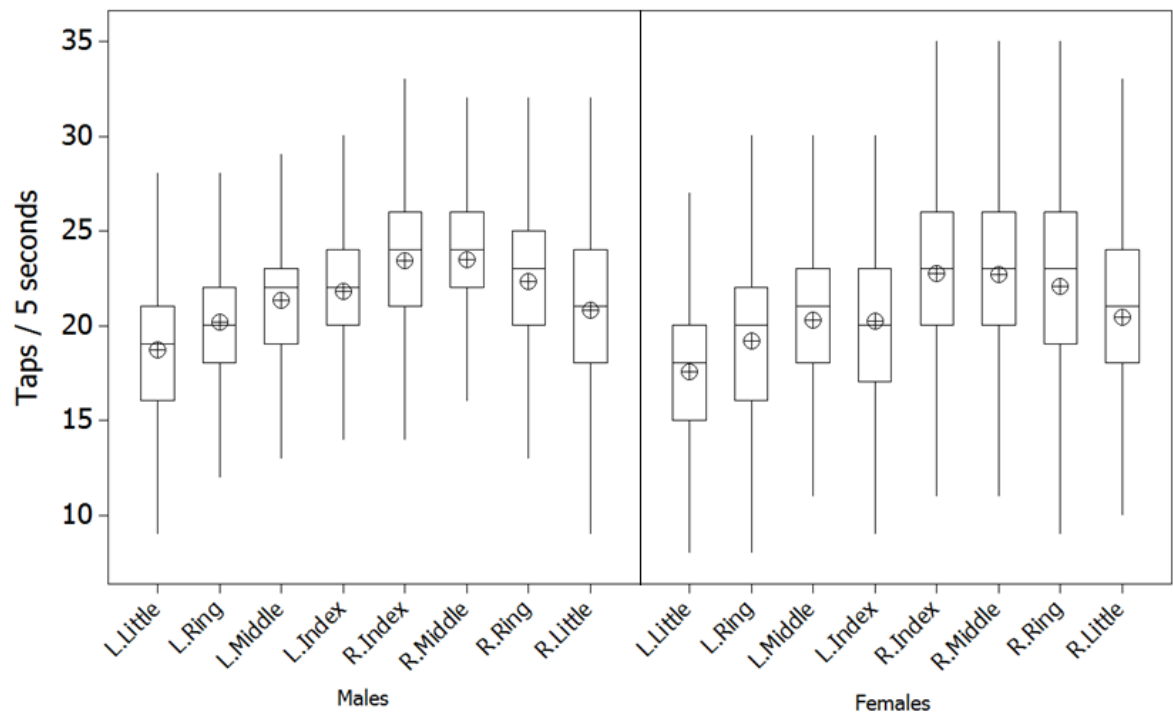


Figure 5.1. Boxplot of finger tapping rate data stratified by finger and gender

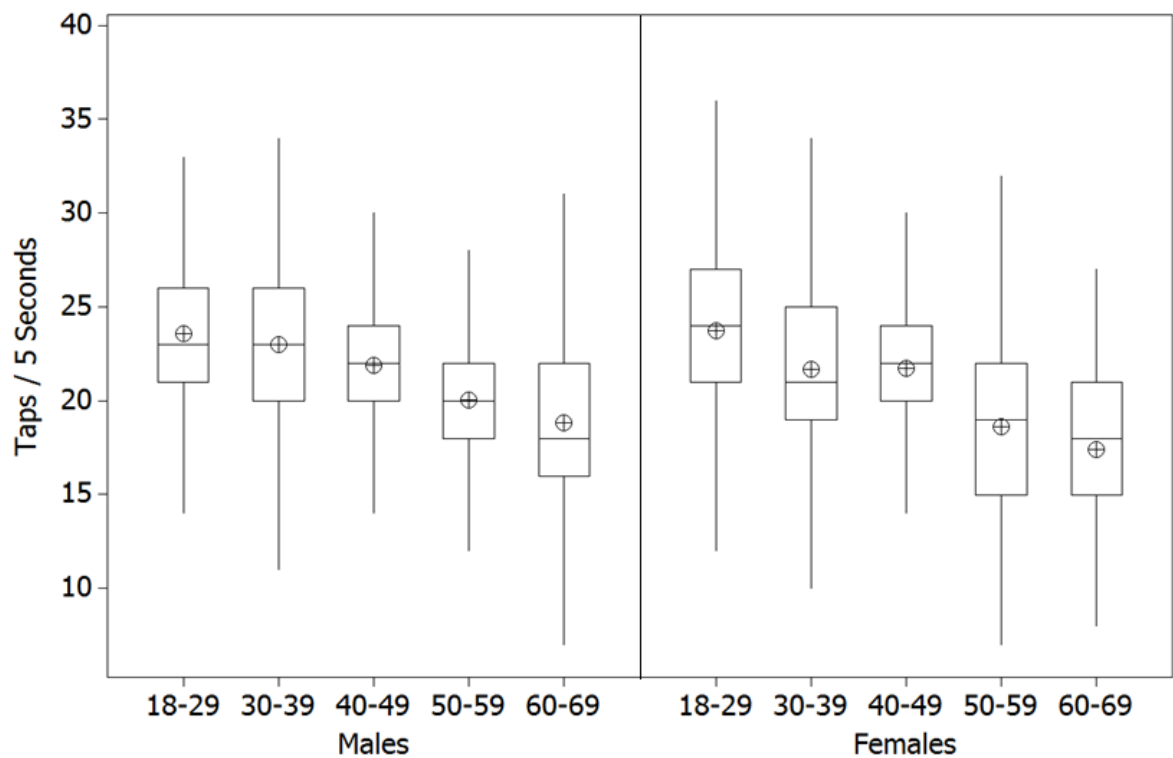


Figure 5.2. Boxplot of finger tapping rate data stratified by age and gender

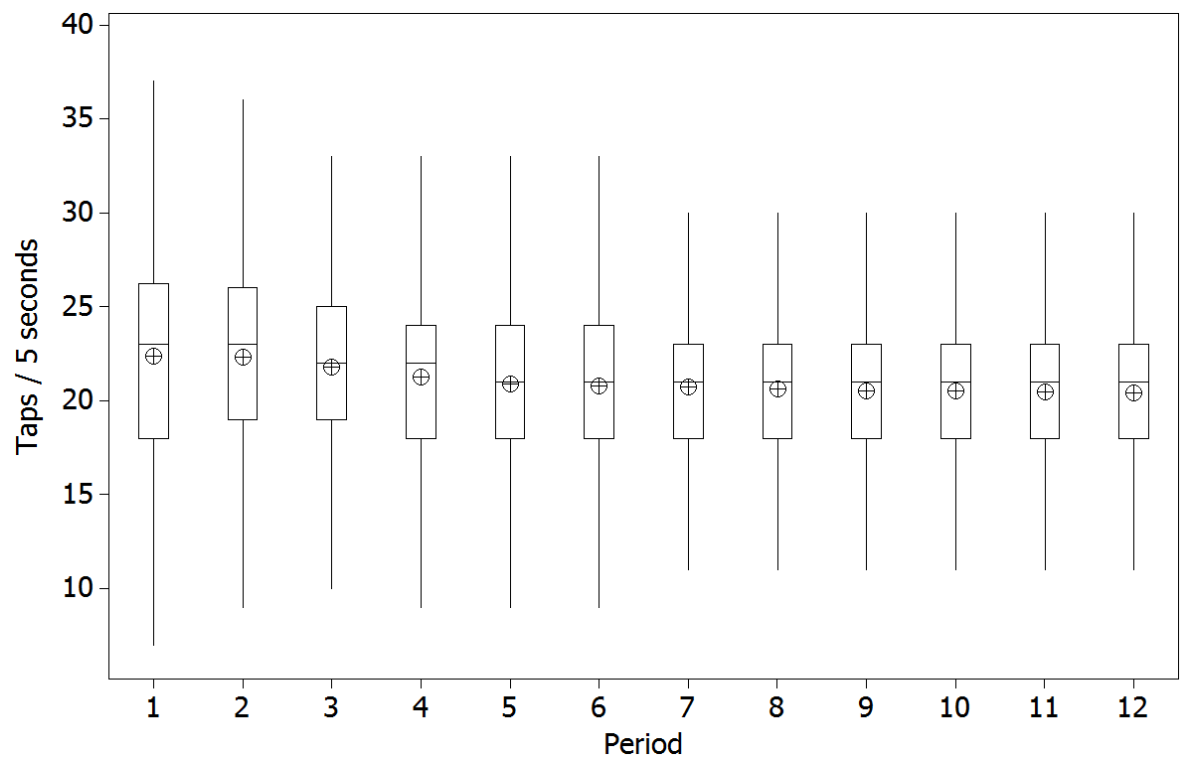


Figure 5.3. Boxplot of finger tapping rate data stratified by period

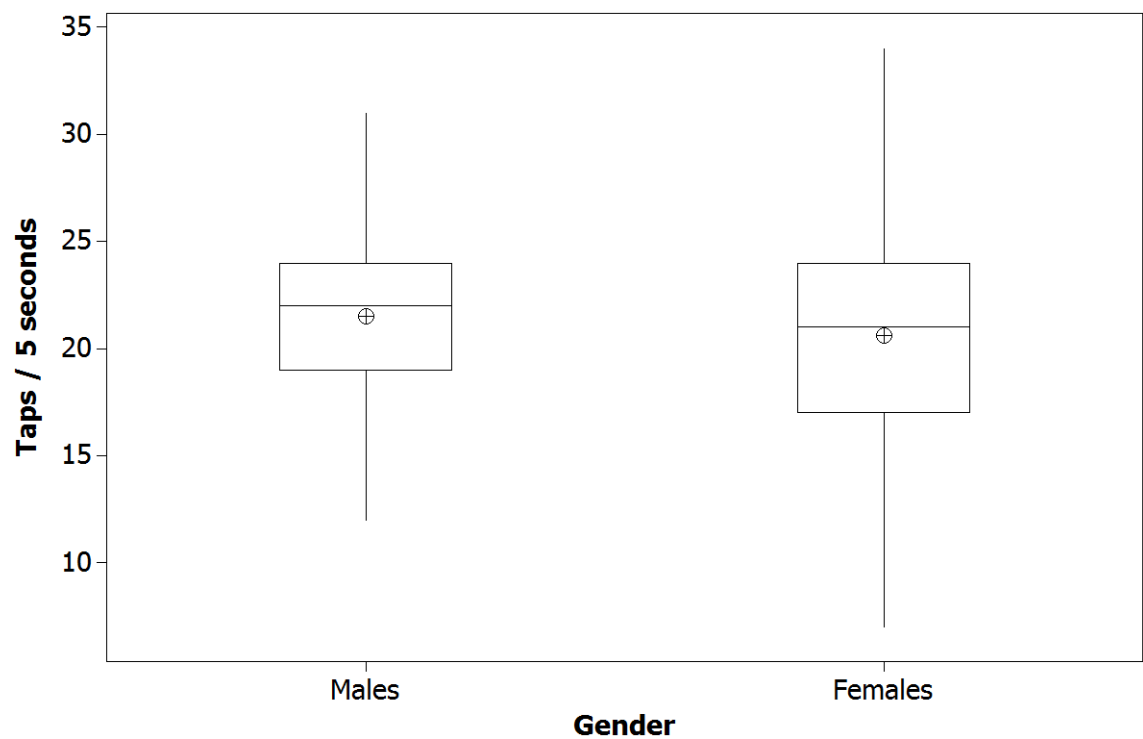


Figure 5.4. Boxplot of finger tapping rate data for gender

Table 5.2. Mean, standard deviation and range values of the tapping rate (number of taps / 5 seconds) data according to age, gender and finger combinations

	18-29		30-39		40-49		50-59		60-69	
	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male
	$\bar{x} \pm s$ (range)		$\bar{x} \pm s$ (range)		$\bar{x} \pm s$ (range)		$\bar{x} \pm s$ (range)		$\bar{x} \pm s$ (range)	
Left little	19.0 $\pm$ 3.3 (10 - 27)	20.0 $\pm$ 2.8 (14 - 28)	18.9 $\pm$ 3.8 (10 - 27)	19.4 $\pm$ 3.7 (11 - 32)	18.2 $\pm$ 3.8 (9 - 28)	18.3 $\pm$ 2.9 (8 - 25)	16.9 $\pm$ 3.7 (10 - 25)	17.8 $\pm$ 3.6 (9 - 28)	14.8 $\pm$ 3.5 (5 - 24)	16.8 $\pm$ 4.3 (7 - 27)
Left ring	21.5 $\pm$ 3.4 (11 - 30)	21.5 $\pm$ 2.6 (16 - 28)	19.5 $\pm$ 3.4 (11 - 29)	20.2 $\pm$ 3.2 (13 - 29)	20.0 $\pm$ 2.6 (14 - 27)	20.4 $\pm$ 3.5 (9 - 28)	18.0 $\pm$ 4.5 (8 - 28)	19.0 $\pm$ 3.7 (11 - 29)	16.5 $\pm$ 3.4 (10 - 25)	18.0 $\pm$ 3.6 (11 - 28)
Left middle	22.6 $\pm$ 2.9 (16 - 32)	22.1 $\pm$ 2.3 (17 - 30)	21.7 $\pm$ 3.7 (14 - 30)	21.8 $\pm$ 3.6 (12 - 33)	21.2 $\pm$ 2.5 (15 - 28)	21.3 $\pm$ 2.2 (16 - 31)	18.3 $\pm$ 4.7 (7 - 27)	20.4 $\pm$ 3.3 (13 - 29)	17.5 $\pm$ 3.7 (8 - 25)	19.2 $\pm$ 4.2 (11 - 30)
Left index	22.6 $\pm$ 3.3 (14 - 33)	22.6 $\pm$ 2.5 (16 - 30)	21.3 $\pm$ 3.4 (14 - 30)	22.4 $\pm$ 3.7 (16 - 33)	20.5 $\pm$ 2.6 (15 - 29)	22.0 $\pm$ 1.9 (18 - 28)	19.1 $\pm$ 5.0 (9 - 29)	20.9 $\pm$ 2.3 (9 - 27)	17.0 $\pm$ 3.6 (9 - 24)	19.3 $\pm$ 3.7 (7 - 28)
Overall Left Hand	21.6 $\pm$ 3.5 (10 - 33)	22.1 $\pm$ 3.3 (14 - 36)	20.4 $\pm$ 3.7 (10 - 30)	21.5 $\pm$ 3.8 (11 - 33)	20.6 $\pm$ 3.7 (9 - 31)	20.8 $\pm$ 3.2 (8 - 31)	17.6 $\pm$ 4.5 (7 - 29)	19.6 $\pm$ 3.5 (9 - 29)	16.5 $\pm$ 3.7 (5 - 25)	18.3 $\pm$ 4.1 (7 - 30)
Right index	27.5 $\pm$ 3.6 (17 - 36)	25.6 $\pm$ 3.2 (19 - 37)	24.4 $\pm$ 3.7 (17 - 35)	25.4 $\pm$ 3.0 (18 - 34)	23.6 $\pm$ 2.4 (16 - 32)	24.5 $\pm$ 2.5 (20 - 33)	20.4 $\pm$ 5.0 (10 - 31)	21.9 $\pm$ 3.3 (14 - 28)	19.0 $\pm$ 4.3 (9 - 26)	19.8 $\pm$ 4.1 (12 - 30)
Right middle	26.7 $\pm$ 3.1 (18 - 34)	26.0 $\pm$ 3.2 (20 - 37)	24.3 $\pm$ 3.5 (19 - 34)	26.1 $\pm$ 3.1 (20 - 36)	23.7 $\pm$ 2.8 (15 - 31)	24.4 $\pm$ 2.4 (19 - 31)	20.9 $\pm$ 5.0 (10 - 32)	21.0 $\pm$ 4.1 (12 - 28)	19.1 $\pm$ 4.3 (9 - 27)	20.3 $\pm$ 4.2 (12 - 33)
Right ring	26.1 $\pm$ 3.5 (16 - 35)	24.2 $\pm$ 3.2 (17 - 35)	23.6 $\pm$ 3.9 (17 - 31)	24.7 $\pm$ 2.8 (19 - 32)	23.6 $\pm$ 2.7 (16 - 33)	23.0 $\pm$ 2.4 (16 - 30)	20.9 $\pm$ 5.2 (9 - 30)	19.9 $\pm$ 3.5 (12 - 27)	18.0 $\pm$ 4.0 (9 - 25)	20.0 $\pm$ 4.1 (12 - 32)
Right little	24.2 $\pm$ 3.3 (16 - 33)	23.6 $\pm$ 3.0 (18 - 35)	21.5 $\pm$ 3.8 (14 - 32)	22.8 $\pm$ 4.0 (15 - 32)	20.8 $\pm$ 3.2 (11 - 30)	21.3 $\pm$ 3.3 (12 - 30)	19.6 $\pm$ 4.7 (10 - 30)	19.4 $\pm$ 3.5 (12 - 27)	17.3 $\pm$ 3.7 (10 - 25)	17.3 $\pm$ 4.1 (9 - 27)
Overall Right Hand	25.9 $\pm$ 3.6 (16 - 36)	25.0 $\pm$ 3.3 (14 - 36)	23.0 $\pm$ 4.2 (14 - 35)	24.4 $\pm$ 3.5 (15 - 36)	22.9 $\pm$ 3.0 (11 - 33)	23.0 $\pm$ 3.1 (12 - 33)	19.6 $\pm$ 5.2 (9 - 32)	20.6 $\pm$ 3.7 (12 - 28)	18.3 $\pm$ 4.2 (9 - 27)	19.3 $\pm$ 4.3 (9 - 33)
Overall (F and M)	23.7 $\pm$ 3.9 (10 - 37)		22.3 $\pm$ 4.1 (10 - 36)		21.8 $\pm$ 3.4 (8 - 33)		19.3 $\pm$ 4.5 (7 - 32)		18.1 $\pm$ 4.2 (5 - 33)	
Overall	21.1 $\pm$ 4.5 (5 - 37)									

The results for the subjective ratings for the fatigue in the fingers according to 10 points Borg's ratings of perceived exertion scale (Borg, 1998) is given in Table 5.3. By looking at the standard deviation values in Table 5.3, it seems that rating of perceived exertion is very variable between the subjects for the fatigue after one minute tapping task. However, there is still a trend. Fatigue decreases when moving from little to index fingers and left hand fingers are more prone to fatigue. It seems that the fingers which tapped more than others have also less fatigue than the others. For instance, on average right index finger tapped the highest number of times in one minute, however still had the smallest fatigue after one minute.

Table 5.3. Mean and standard deviation values for the rating of perceived exertion after one minute tapping for each finger.

Fingers	$\bar{x}$	s
Left Little	3.1	2.0
Left Ring	2.9	2.0
Left Middle	2.3	1.8
Left Index	1.9	1.7
Right Index	1.5	1.7
Right Middle	1.9	1.7
Right Ring	2.2	1.8
Right Little	2.5	1.9
Grand Total	2.3	1.9

Another result according to use of Borg's scale is that fatigue after one minute tapping is light or moderate. The highest mean fatigue value which is 3.1 for left little finger corresponds to "moderate" fatigue (see Table 5.3). This means that most of the subjects can carry on tapping more than one minute.

5.1.1.3. Inferential Statistics. An ANOVA model and post-hoc analyses using Tukey tests are performed to investigate the effects of the factors on tapping rate. Besides the main factors, interaction effects are also investigated, however none are found significant. So, only the main factors without the interaction terms are used in the model. Below is the equation of the used general linear model.

$$y_{ijklmn} = \mu + \alpha_i + \beta_j + \gamma_k + \delta_l + \theta_m + \rho_n + \varepsilon_{ijklmn}$$

where

y_{ijklmn} : the response variable (number of keystrokes per 5 seconds)

μ : the overall response mean

α_i : the effect of the age level i ($i = 18-19, 30-39, 40-49, 50-59, 60-69$)

β_j : the effect of the gender j ($j = \text{female, male}$)

γ_k : the effect of the finger k ($k = \text{left little, left ring, left middle, left index, right index, right middle, right ring, right little}$)

δ_l : the effect of the l th period ($l = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12$)

θ_m : the effect of the smoking level m ($m = \text{smoker, non smoker}$)

ρ_n : the effect of the exercise level n ($n = \text{exercising, not exercising}$)

ε_{ijklmn} : the usual random error term

According to ANOVA model results, all factors are found to be significant. The results of the ANOVA model as taken from Minitab 16 statistical software package is shown in Table 5.4 and coefficients table for the factors is given in Table 5.5.

Table 5.4. ANOVA results table for monograph experiments.

Source of variation	Degrees of freedom	Seq SS	Adj SS	Adj MS	F	p
Age	4	49829	48587	12147	975.62	0.00
Fingers	7	29853	29752	4250	341.38	0.00
Periods	11	5434	5412	492	39.51	0.00
Smoking	1	5502	4376	4376	351.50	0.00
Exercise	1	5111	4275	4275	343.37	0.00
Gender	1	375	375	375	30.10	0.00
Error	11787	146751	146751	13		
Total	11812	242854				

S = 3.53 R-Sq = 39.57% R-Sq(adj) = 39.44%

Table 5.5. Coefficients table for the factors in ANOVA.

Term	Coefficient	SE coefficient	t	p
Constant	21.56	0.04	524.80	0.00
Age				
18-29	2.80	0.07	42.31	0.00
30-39	0.88	0.07	12.49	0.00
40-49	0.98	0.07	14.71	0.00
50-59	-1.64	0.07	-26.35	0.00
60-69	-3.02			
Fingers				
Left Little	-2.93	0.09	-34.15	0.00
Left Ring	-1.39	0.09	-16.20	0.00
Left Middle	-0.28	0.09	-3.22	0.00
Left Index	-0.08	0.09	-0.94	0.40
Right Index	2.01	0.09	23.41	0.00
Right Middle	2.00	0.09	23.32	0.00
Right Ring	1.13	0.09	13.09	0.00
Right Little	-0.46			
Periods				
1	1.30	0.11	12.00	0.00
2	1.25	0.11	11.54	0.00
3	0.72	0.11	6.68	0.00
4	0.19	0.11	1.80	0.07
5	-0.16	0.11	-1.44	0.15
6	-0.24	0.11	-2.28	0.02
7	-0.33	0.11	-3.06	0.00
8	-0.43	0.11	-3.97	0.00
9	-0.52	0.11	-4.80	0.00
10	-0.52	0.11	-4.83	0.00
11	-0.61	0.11	-5.64	0.00
12	-0.65			
Smoking				
Non smokers	-0.81	0.04	-18.75	0.00
Smokers	0.81			
Exercise				
Exercising	0.63	0.03	18.53	0.00
Not exercising	-0.63			
Gender				
Males	0.18	0.03	5.49	0.00
Females	-0.18			

Using the model coefficients in Table 5.5, tapping rates can be estimated as a function of the investigated factors. For instance, in order to estimate the tapping rate of a 64 years old woman's right index finger in the first 5 seconds (assuming she smokes and does not exercise regularly), one can use the coefficients in Table 5.5 in such a way: $(21.56 - 3.02 + 2.01 + 1.30 + 0.81 - 0.63 - 0.18 = 21.85 \text{ taps/5 seconds})$. However as explained earlier, these coefficients are for estimating the tapping rates in periods of 5 seconds. For estimating the tapping rate as taps/second, the result should be divided by 5.

To find the prediction interval which 95% of this type of observations will fall in, one should add and subtract $\sqrt{\text{MSE}} * z_{0.975}$ ($3.53 * 1.96 = 6.92$) from this point estimate. For the same example, the prediction interval is 21.85 ± 6.92 .

Post-hoc analyses with Tukey tests with 95% confidence are also performed. The results for post-hoc analysis are given in Table 5.6.

Table 5.6. Grouping information using Tukey method and 95.0% confidence for the considered factors

Age	N	Mean	Grouping	
18-29	2580	24.36	A	B
40-49	2281	22.53		
30-39	2099	22.44		
50-59	2674	19.92		
60-69	2179	18.54		
Finger	N	Mean	Grouping	
Right index	1480	23.57	A	B
Right middle	1475	23.56		
Right ring	1472	22.69		
Left index	1478	21.48		
Left middle	1482	21.28		
Right little	1481	21.11		
Left ring	1469	20.16		
Left little	1476	18.63		
Periods	N	Mean	Grouping	
1	966	22.86	A	B
2	978	22.81		
3	980	22.28		
4	984	21.75		

Table 5.6. Grouping information using Tukey method and 95.0% confidence for the considered factors (cont.).

Periods (cont.)	N	Mean	Grouping	
5	985	21.40	C	D
6	988	21.31	C	D
7	987	21.23		D
8	989	21.13		D
9	991	21.04		D
10	988	21.04		D
11	989	20.95		D
12	988	20.89		D
Smoking	N	Mean	Grouping	
Smokers	2375	22.37	A	
Non smokers	9438	20.74		B
Exercise	N	Mean	Grouping	
Exercising	5534	22.19	A	
Not exercising	6279	20.93		B
Gender	N	Mean	Grouping	
Males	5726	21.74	A	
Females	6087	21.37		B
Means that do not share a common letter are significantly different.				

The effect of a factor is defined to be the change in response produced by a change in the level of the factor. This is frequently called a main effect because it refers to the primary factors of interest in the experiment (Montgomery, 2001). Main effects plots visualizing the effects of categorized factors are shown through Figures 5.5 to 5.10. In all of these graphs, the y axis is converted into interkey stroke times by dividing 5000 msec (5 seconds) to the response (number of keystrokes / 5 seconds).

According to the statistical results, age group is found one of the most defining factors in finger tapping. Overall, the finger tapping rate decreases nonlinearly with increasing age-group (from 18-29 to 69). As seen in Table 5.6 and Figure 5.5, there is a large difference between the groups (18-29) and (30-39). However, between the groups (30-39) and (40-49), this difference is insignificant. Moreover, after age of 50, tapping rate

decreases rapidly. The subjects within the age group of 60-69 years have tapping rate 0.80 taps/sec lower than the subjects within (40-49) age-group.

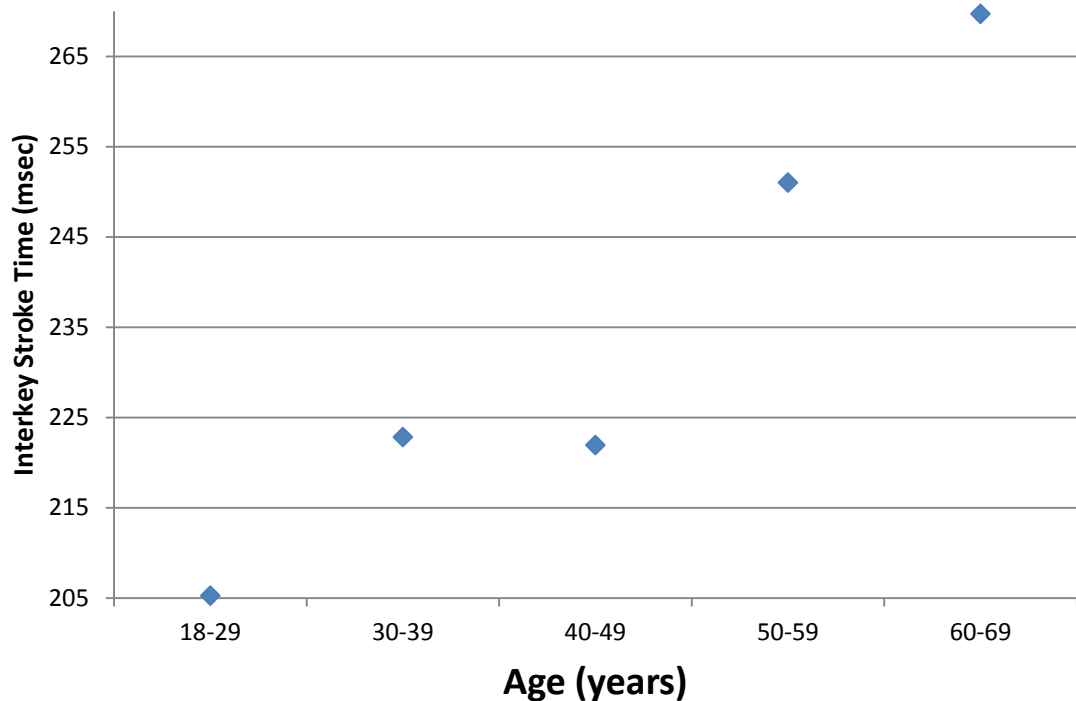


Figure 5.5. Main effect plot for age factor.

Finger is found another important factor significantly affecting tapping rate. As seen from Table 5.6 and Figure 5.6, index and middle fingers were the fastest fingers for both hands and the little fingers the slowest. There was no significant difference between index and middle fingers and this was true for both hands.

All right hand fingers, except little finger, had higher tapping rates than the fingers of left hand. The slowest finger of right hand, the little finger, had nearly the same tapping rate of the fastest fingers of left hand; index and middle fingers (see Table 5.6 and Figure 5.6). Although the absolute tapping rates obtained through the current study are somewhat different from the rates reported by Jackson (1953), the speed order of fingers are similar between the two studies.

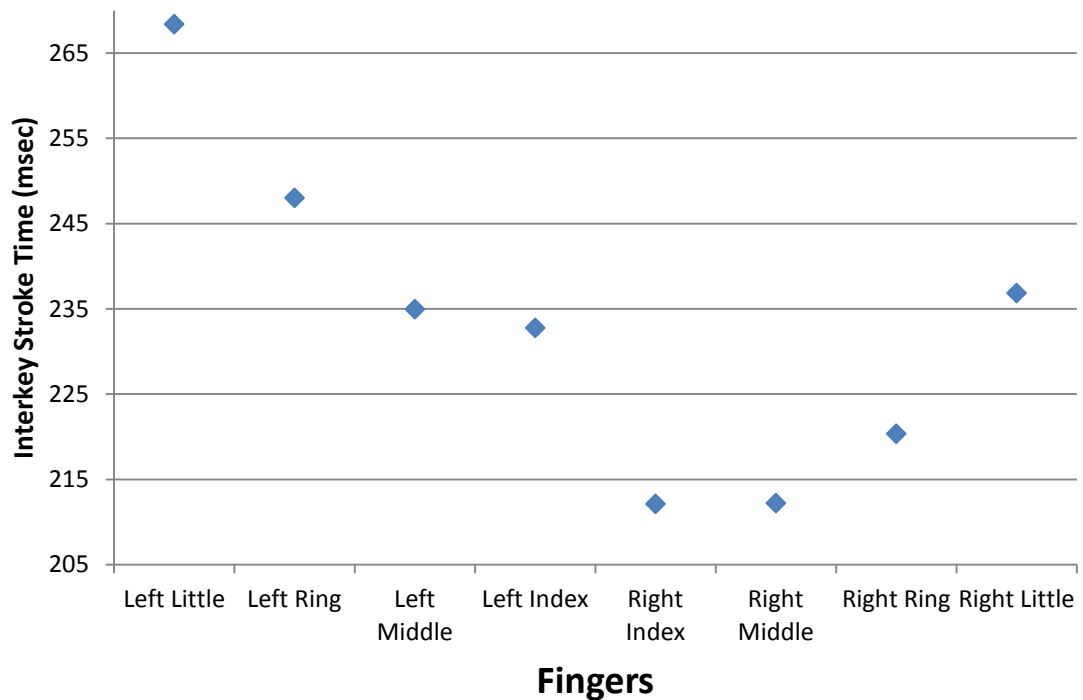


Figure 5.6. Main effect plot for the finger factor.

For the effect of period factor, in general, there is a decreasing trend in the tapping rate from the first period to the last as shown in Figure 5.7. However, as can be seen in Table 5.6, there is no significant difference between period 1 and period 2 (in first 10 seconds). Then, significant decrease occurs for 3rd and 4th periods. Then again, there are no significant differences among 4th through 6th periods. 5th through 12th periods, the differences are also insignificant. It seems that the last 30 seconds of 1 minute tapping task, there is a nearly steady rate of tapping. Since most of the tapping studies in the literature used only one period of 10 seconds, the results obtained from this study cannot be used for comparisons for the period effect.

Smoking is another factor significantly affecting tapping rate (see Table 5.6). The finger tapping rates increased with smoking. Smokers have a finger tapping rate which is 0.32 taps/sec (1.62 taps/5 seconds) higher than non smokers. This result supports the results of previous studies (Silver *et al.*, 2002; Perkins *et al.*, 1990; Roth and Batting, 1991) on the effect of smoking and nicotine on finger tapping rates.

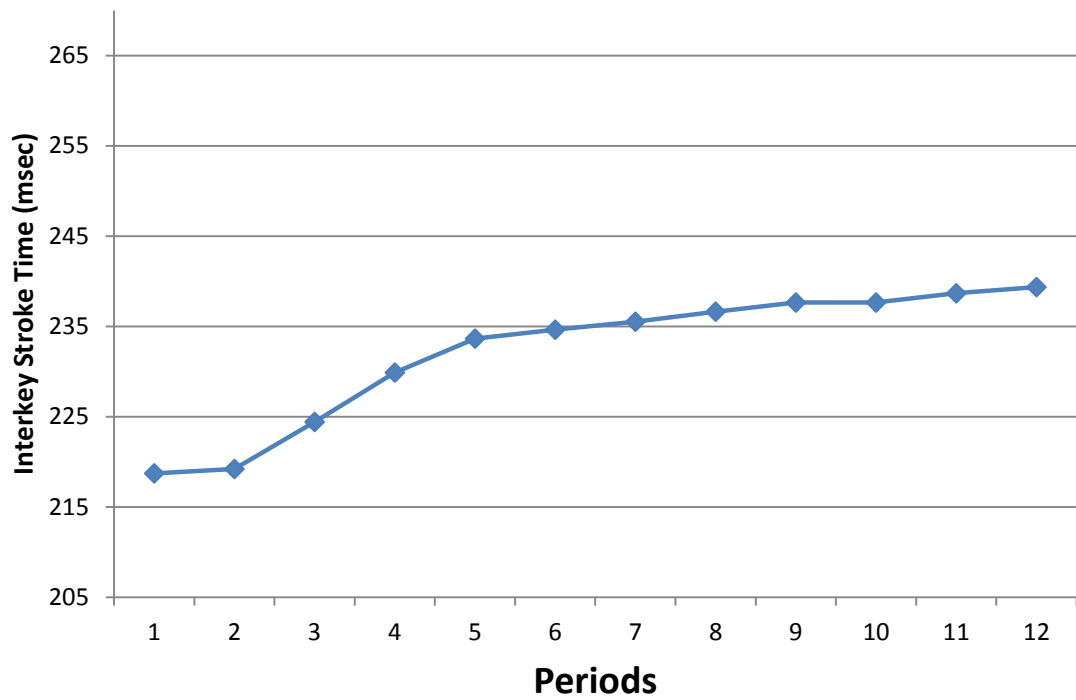


Figure 5.7. Main effect plot for the period factor.

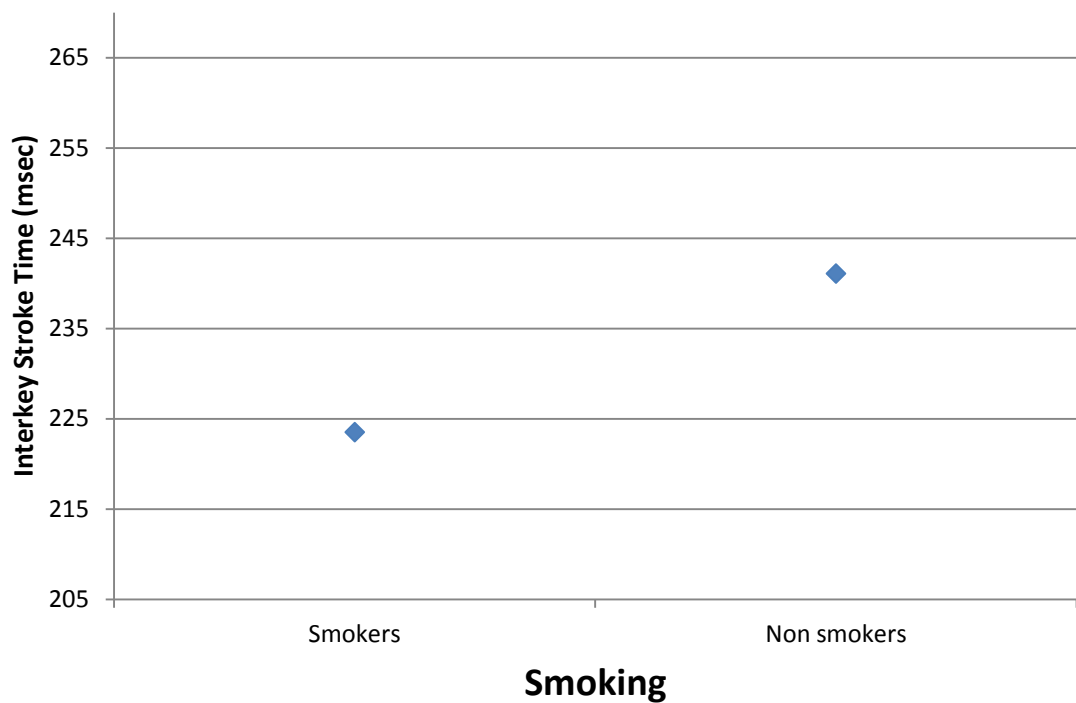


Figure 5.8. Main effect plot for the smoking factor.

Regular exercise is also found statistically significant (see Table 5.6). Subjects who regularly exercise have a higher finger tapping rate than the subjects who do not. This difference is 1.26 taps/5 seconds (0.25 taps/second).

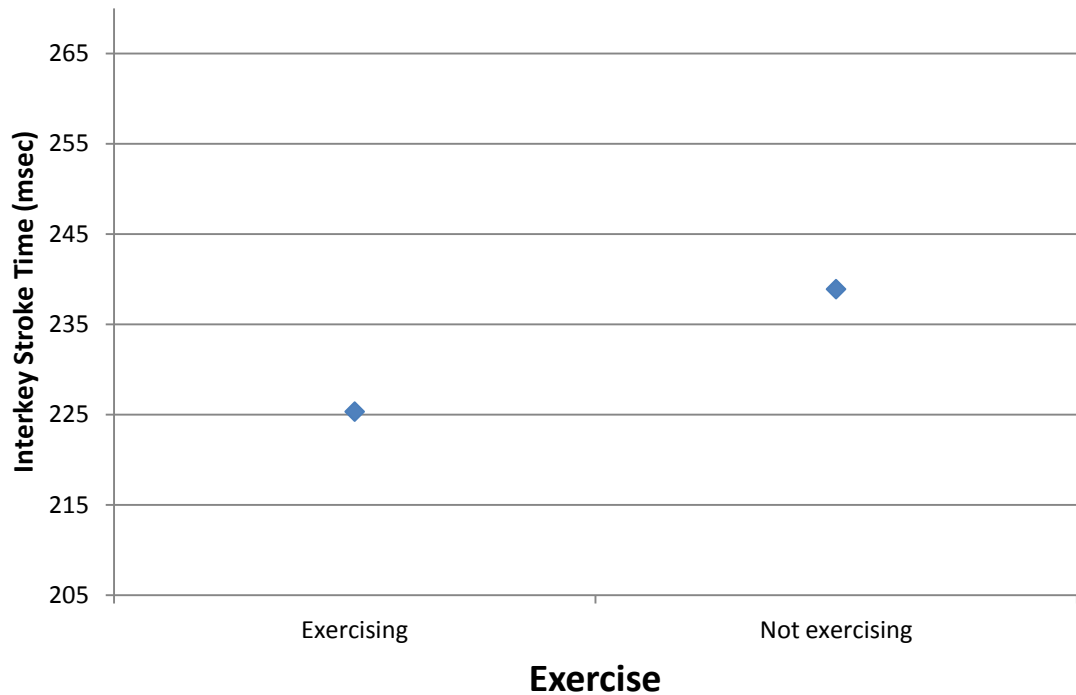


Figure 5.9. Main effect plot for the exercise factor.

Males were found to have statistically higher tapping rates than females (0.36 taps/5 seconds). Although this effect was statistically significant, the difference, only 0.07 taps/sec, may be considered insignificant in practical sense (see Table 5.6 and Figure 5.10). This result is in agreement with the study by Schmidt *et al.* (2000). However, the magnitude of the difference in their study was higher, 0.32 taps/sec, between the right-hand dominant male and female university students. This difference in experimental results may partly arise from the characteristics of the participants like age, nationality, etc.

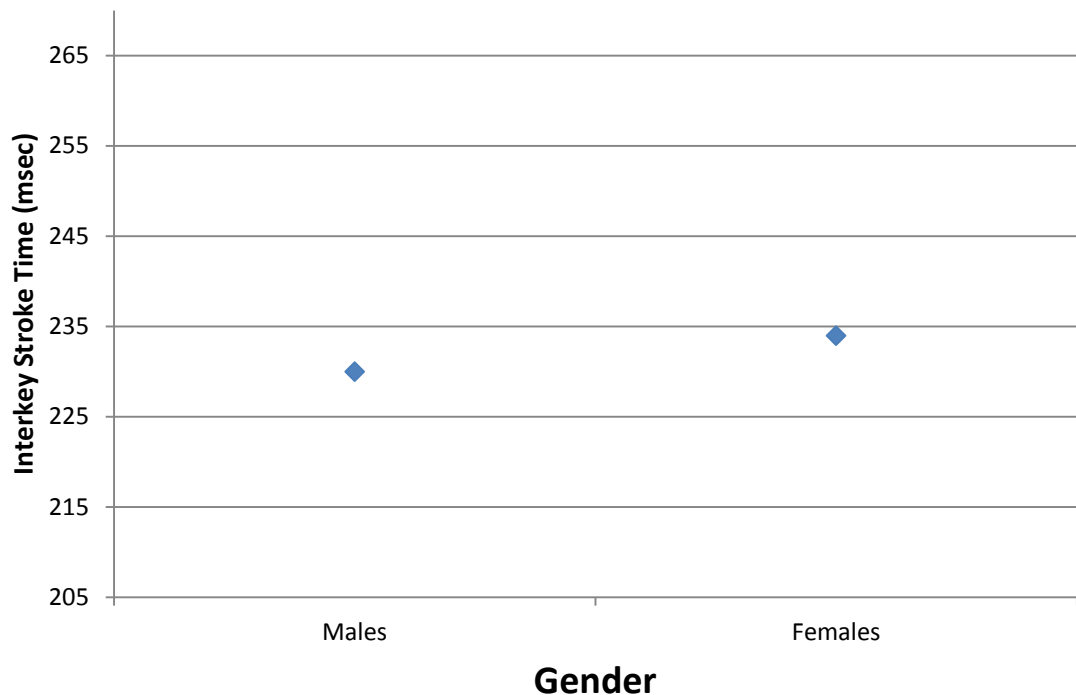


Figure 5.10. Main effect plot for the gender factor.

5.1.2. Determining Tapping Rate Capacity of Fingers

The main aim of this experiment is calculating the tapping rate capacity of fingers which are used in quantifying the monograph penalty scores. The ergonomic design for fingers obviously should distribute the task loads to the fingers according to their capacity.

5.1.2.1. Response Variable and Investigated Independent Variables. In order to calculate the tapping rate capacity for each finger, another ANOVA model is formed by describing the subjects as the block factor; and period and finger as the factors. The dependent variable is the same as before (number of keystrokes per 5 seconds, see Table 5.7). In the previous analysis in Section 5.1.1, the effects of the characteristics of the subjects such as age, gender, smoking, etc are investigated. However, for determining the tapping rate capacity of fingers, the only important factor is the finger factor. So in order to increase the explanatory power of the ANOVA, all the characteristics of the subjects were discarded by blocking the subjects.

Table 5.7. Dependent and independent variables and their levels used in the statistical analysis

	Name	Levels
Dependent variable	Number of keystrokes per 5 seconds	
Independent variables	Subjects (block)	
	Fingers	Left little, Left ring, Left middle, Left index, Right index, Right middle, Right ring, Right little
	Periods	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12

5.1.2.2. Inferential Statistics. Below is the mathematical equation of the used statistical model.

$$y_{ijk} = \mu + \beta_i + \alpha_j + \gamma_k + \varepsilon_{ijk}$$

where

y_{ijk} : the response variable (number of keystrokes per 5 seconds)

μ : the overall response mean

β_i : the effect of the i th subject (block factor)

α_j : the effect of the j th period ($j = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12$)

γ_k : the effect of the finger k ($k =$ left little, left ring, left middle, left index, right index, right middle, right ring, right little)

ε_{ijk} : the usual random error term

In this model, effect of the subjects is a nuisance factor: a factor that has an effect on the response, but we are not interested in that effect (Montgomery, 2001). In order to eliminate its effect on the statistical comparisons, subjects are blocked. Because of this blocking, ANOVA has a higher R^2 value. This way, the tapping rate capacities of fingers are estimated more precisely. The ANOVA table for this model is shown in Table 5.8.

To obtain the tapping rate capacity of fingers, main effects of each finger (see Table 5.9) in the ANOVA are normalized against 100%. For instance; for left little finger, the corresponding coefficient can be calculated as such $((17.98 / (17.98 + 19.52 + 20.60 + 20.75 + 23.17 + 23.22 + 22.25 + 20.82)) * 100 = 10.7)$. The resulting parameters show the normalized tapping rates of each finger with respect to total (Table 5.10). Table 5.10 also

enlists the normalized parameters that are used by Dvorak *et al.* (1936). These parameters are also based on tapping rate and they are directly taken from Dvorak *et al.* (1936). When these values are compared, it is seen that the order of the fingers is the same and there are small differences in the values. Our parameters are a little higher for the little and ring fingers while Dvorak's parameters are a little higher for index and middle fingers. Also the difference between left and right hands according to our parameters are higher than the difference in Dvorak's parameters.

Table 5.8. ANOVA results table

Source of variation	Degrees of freedom	Seq SS	Adj SS	Adj MS	F	p
Subjects (Block)	114	126484	126665	1111	224.02	0.00
Fingers	7	30998	30955	4422	891.58	0.00
Periods	11	5462	5462	497	100.11	0.00
Error	10790	53517	53517	5		
Total	10922	216461				

S = 2.23 R-Sq = 75.28% R-Sq(adj) = 74.97%

Table 5.9. Main effects table for the fingers which shows the number of keystrokes pressed by the associated finger in 5 seconds.

Finger	Main Effects
L. Little	17.98
L. Ring	19.52
L. Middle	20.60
L. Index	20.75
R. Index	23.17
R. Middle	23.22
R. Ring	22.25
R. Little	20.82

As explained before in Section 4.2, monograph penalty score of a keyboard layout is calculated by summing the absolute differences between the desired target loads (tapping rate capacities of fingers) that are listed in Table 5.10 and actual loads for each of the eight fingers in a given keyboard layout.

Table 5.10. Normalized tapping rates of fingers which are now called as tapping rate capacity of fingers (desired target loads on the fingers).

Finger	Normalized Tapping Rates (%)	Dvorak <i>et al.</i> (%)
Left Little	*10.7	10
Left Ring	11.6	11
Left Middle	12.2	13
Left Index	12.3	13.5
Right Index	13.8	14
Right Middle	13.8	14
Right Ring	13.2	13
Right Little	12.4	11.5

*Numbers add up to 100%.

In Table 5.11, there is an example calculation for the monograph penalty of Turkish F keyboard layout. Actual load in a given layout for a specified finger is calculated by summing the monograph frequencies of the letters that are assigned to the keys operated by the specified finger. The sum of all absolute differences of fingers between the actual loads in F layout and desired target loads is the monograph penalty of Turkish F layout according to Turkish language. This total is 39.9% which is a high value stating that there is a 39.9% deviation from the desired target loads across all fingers in Turkish F layout while typing in Turkish language.

Table 5.11. The calculation of monograph penalty of Turkish F keyboard layout for Turkish language. The actual load distribution of fingers is calculated from the monograph frequencies in Turkish National Corpus.

	Left Little	Left Ring	Left Middle	Left Index	Right Index	Right Middle	Right Ring	Right Little	Total
Actual Load	3.7%	11.5%	12.0%	22.4%	23.6%	13.8%	7.4%	5.6%	100%
Desired Target Load	10.7%	11.6%	12.2%	12.3%	13.8%	13.8%	13.2%	12.4%	100%
Absolute Difference	7.0%	0.1%	0.2%	10.1%	9.9%	0.0%	5.8%	6.8%	39.9%

5.1.3. Power Analysis

After the experiments, a power analysis is done in order to define the power of the tests that are done for the estimation of finger tapping rates. Standard deviation of the

response (number of keystrokes in 5 seconds) between the subjects in a specified finger is estimated as 4.0. Using this standard deviation, a power curve (see Figure 5.11) is generated in MiniTab 16 using a two sample t test. This power curve shows the power in which two fingers can be separated from each other ($H_0: \mu_1 = \mu_2$).

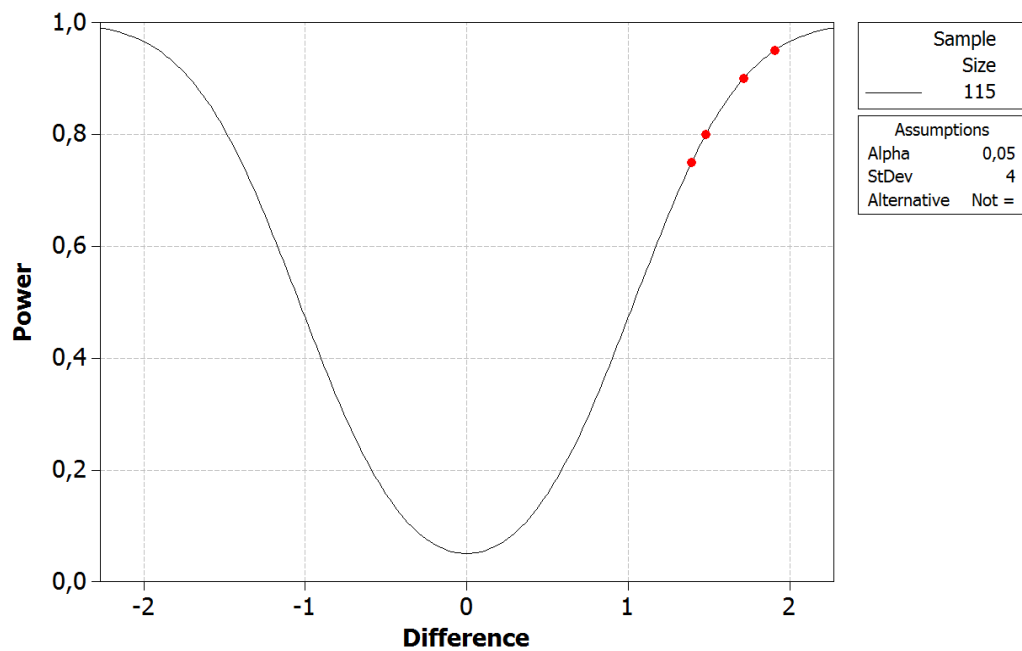


Figure 5.11. Power curve for the experiments to estimate the finger tapping rates

As seen from Figure 5.11, with 115 subjects and 75% power, we can detect a difference of 1.4 keystrokes per 5 seconds between two fingers. In other words, if there is 0.3 keystrokes per second difference between the fingers in reality, with our experiments we can detect it 75% of the time. This is the power of our monograph experiments.

5.2. Results of Experimental Study II and Calculation of Digraph Penalties

Experimental results for the digraph tapping rates as well as how these results are converted to digraph penalties are explained in this section.

Although the digraph experiment was done with 8 subjects, during the analysis the data from one subject who is left handed is omitted. After the data is analyzed statistically, some of the combinations in which the results have the highest variability between subjects

were detected and repeated by the same subjects. Almost 5% of the experiments were repeated this way.

5.2.1. Factor Effects

Our main goal in conducting these experiments was quantifying the ergonomic criteria for the digraphs that are typed in the keyboard. In addition, some useful information can also be extracted from the experimental results that can help the scientists who work on finger kinematics, anatomy, etc. In this section, the effects of some factors that affect typing speed are investigated.

5.2.1.1. Response Variable and Investigated Independent Variables. In the experiments, randomized block design is used and subjects are blocked. The number of keystrokes in 30 seconds is used as the dependent variable (response). The independent (explanatory) variables are subject factor which is blocked in the experiments, period factor, hand factor, column factor and row factor (see Table 5.12).

Table 5.12. Dependent and independent variables and their levels used in the statistical analysis

	Name	Levels
Dependent variable	Number of correct keystrokes minus number of errors per 30 seconds	
Independent variables	Subjects (block)	
	Periods	1, 2, 3, 4
	Hands	Right, Left
	Columns	C1-C1, C1-C2, C1-C3, C1-C4, C1-C5, C1-C6, C1-C7, C2-C2, C2-C3, C2-C4, C2-C5, C2-C6, C2-C7, C3-C3, C3-C4, C3-C5, C3-C6, C3-C7, C4-C4, C4-C5, C4-C6, C4-C7, C5-C5, C5-C6, C5-C7, C6-C6, C6-C7
	Rows	Bottom-Bottom, Top-Bottom, Top-Top, Top-Home, Home-Bottom, Home-Home

As explained in Section 4.6, each experiment lasted 2 minutes. Each experiment is divided into 30 seconds periods. So period factor shows the changes in the response as time proceeds and it has 4 levels.

Hand factor is used to see if there is a difference in the response between left and right hand. In the keyboard assignment studies, there are different applications regarding to hand assignments.

The column factor is used mostly to understand how different fingers interact with each other and the finger kinematics. Since each finger has its own columns in touch typing, the column numbers here also show the fingers that press the associated digraph. Each column has given a name which is shown in Figure 5.12. And digraphs are expressed using the column numbers they contain (see Table 5.12). For instance, digraph_{24,30} (see Figure 5.12) has a column level of “C3-C6” since key 24 is in column 3 and key 30 is in column 6 (see Figure 5.12). Columns are not separated for left and right hands, since hand factor is another factor in the analysis.

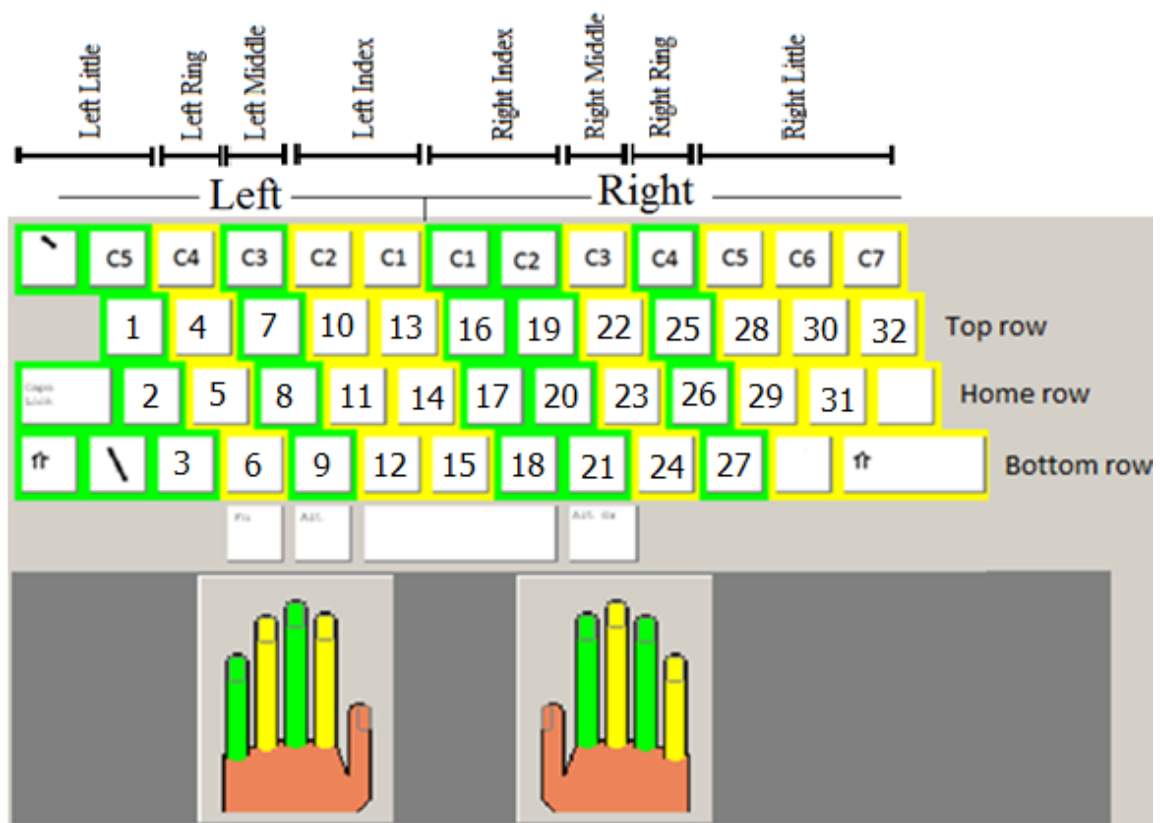


Figure 5.12. Columns and rows on a conventional keyboard.

The row factor is used to understand the movement between rows. A conventional keyboard has three rows: top row, home row and bottom row which can be seen in Figure 5.12. Digraphs are expressed using the rows they contain (see Table 5.12). For instance, digraph_{24,30} (see Figure 5.12) has a row level of “top-bottom” since key 24 is in bottom row and key 30 is in top row.

5.2.1.2. Descriptive Statistics of Response Variable. The collected digraph tapping rate data are summarized by box plots (Figures 5.13 and Figure 5.14). The box plots depict mean (circles), median, 1st and 3rd quartile and range values and spread of the data for rows, columns and hand factors.

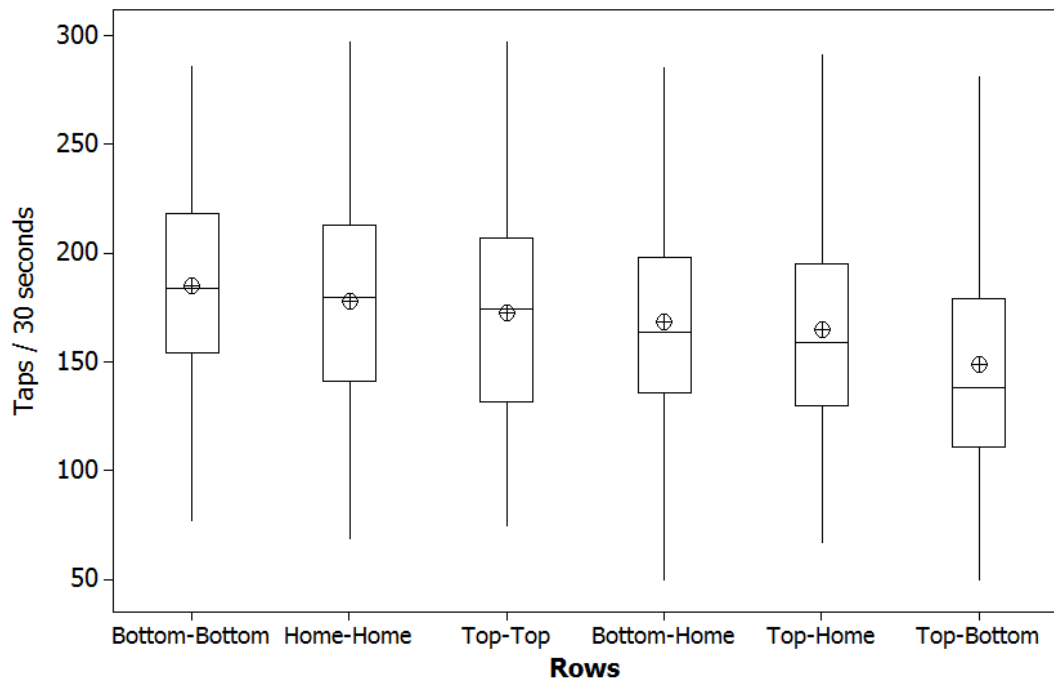


Figure 5.13. Boxplot of digraph typing speed data stratified by rows.

From the Figure 5.13, it seems like digraph tapping rate is fastest when the two keys of the digraph are in the row. However, when there is a reach (moving up or down one row), tapping rate seems to decrease. If there is a hurdle (moving from top to bottom row, or vice versa), then tapping rate seems to decrease even more.

From Figure 5.14, it seems like right hand digraphs has a higher tapping rate than left hand digraphs. Inside each hand, the digraphs that are tapped with the same finger (e.g.,

C1-C2) seem to have the lowest tapping rate while the digraphs that are tapped with the remote fingers (e.g., C1-C4) seem to have the highest tapping rates. Also the digraphs that include the index finger and middle finger (unless both of them are tapped with the same finger) seem to have the highest tapping rate.

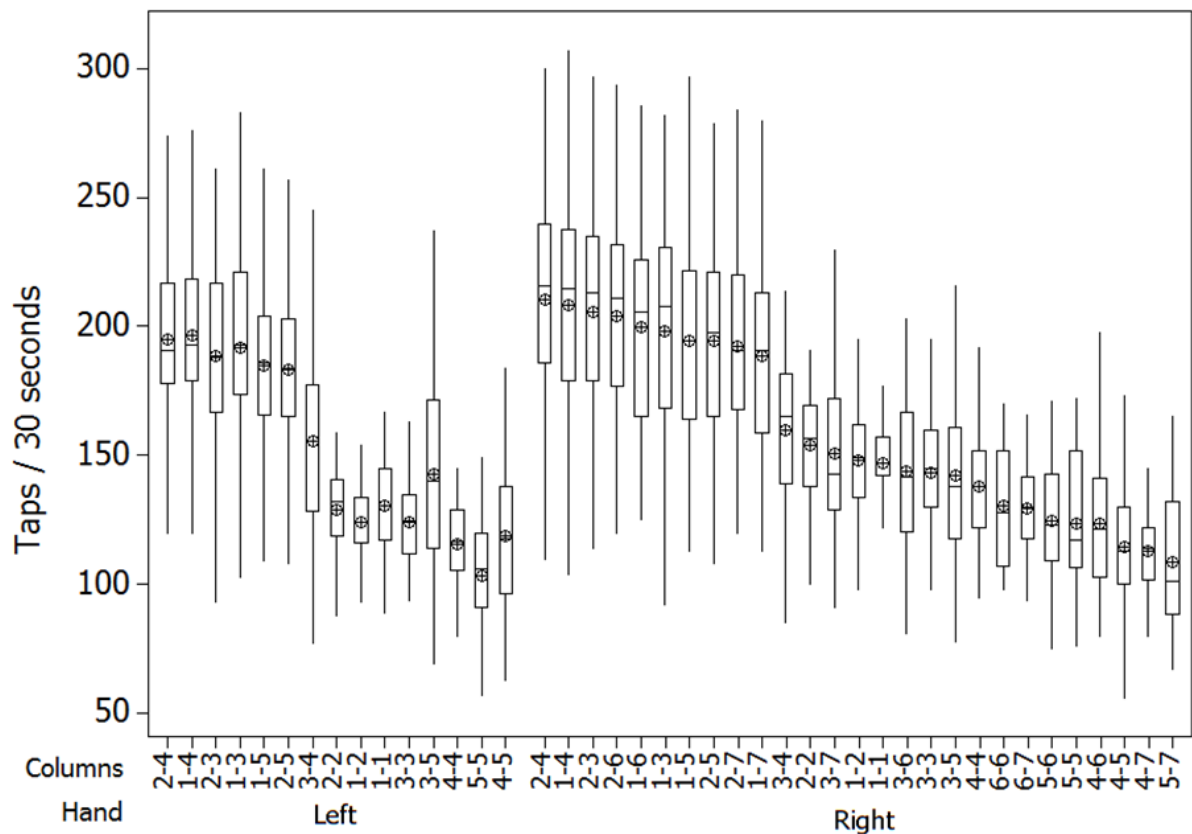


Figure 5.14. Boxplot of digraph typing speed data stratified by hand and columns

5.2.1.3. Inferential Statistics. Statistical analysis on the data is performed using an ANOVA model. Below is the mathematical equation of the general linear model that is used.

$$y_{ijklm} = \mu + \beta_i + \alpha_j + \gamma_k + \delta_l + \theta_m + \rho_n + \varepsilon_{ijklm}$$

where

y_{ijklm} : the response variable (number of keystrokes per 5 seconds)

μ : the overall mean

β_i : the effect of the i th subject (block factor)

α_j : the effect of the j th period ($j = 1, 2, 3, 4$)

γ_k : the effect of the hand k ($k = \text{right, left}$)

δ_l : the effect of the column l ($l = 1-1, 1-2, 1-3, 1-4, 1-5, 1-6, 1-7, 2-2, 2-3, 2-4, 2-5, 2-6, 2-7, 3-3, 3-4, 3-5, 3-6, 3-7, 4-4, 4-5, 4-6, 4-7, 5-5, 5-6, 5-7, 6-6, 6-7$)

θ_m : the effect of the row m ($m = \text{Bottom-Bottom, Top-Bottom, Top-Top, Top-Home, Home-Bottom, Home-Home}$)

ε_{ijklm} : the usual random error term

The statistical result table of the ANOVA model is shown in Table 5.13 and the coefficients' table can be seen in Table 5.14. Post-hoc analyses with Tukey tests with 95% confidence are also performed. The post-hoc analysis of the factors can be found in Table 5.15.

Table 5.13. ANOVA results table.

Source of variation	Degrees of freedom	Seq SS	Adj SS	Adj MS	F	p
Subjects (block)	6	2,510,937	2,500,151	416692	732.58	0.00
Columns	26	7,055,561	6,943,678	267065	469.52	0.00
Rows	5	541721	527251	105450	185.39	0.00
Hand	1	168311	168155	168155	295.63	0.00
Period	3	81334	81334	27111	47.66	0.00
Error	6662	3,789,370	3,789,370	569		
Total	6703	14,147,232				

S = 23.85 R-Sq = 73.21% R-Sq(adj) = 73.05%

According to the ANOVA results, all the factors are statistically significant. However, when the factors are ranked according to their explanatory power, it can be seen that columns factor have the highest explanatory power and subject factor which is blocked

is the second. Other factors although significant, do not have the same explanatory power of either column or subject factor.

Table 5.14. Coefficients table for the factors in ANOVA.

Term	Coefficient	SE coefficient	t	p
Constant	155.25	0.47	332.94	0.00
Columns				
1-1	-10.56	1.83	-5.76	0.00
1-2	-17.04	1.11	-15.31	0.00
1-3	42.06	1.12	37.46	0.00
1-4	49.12	1.11	44.13	0.00
1-5	36.30	1.21	30.02	0.00
1-6	40.04	1.83	21.90	0.00
1-7	32.95	2.58	12.76	0.00
2-2	-7.90	1.83	-4.31	0.00
2-3	44.22	1.12	39.52	0.00
2-4	49.76	1.12	44.63	0.00
2-5	35.60	1.21	29.39	0.00
2-6	44.43	1.83	24.23	0.00
2-7	36.20	2.57	14.10	0.00
3-3	-15.54	1.83	-8.48	0.00
3-4	4.65	1.11	4.17	0.00
3-5	-9.50	1.22	-7.80	0.00
3-6	-15.34	1.84	-8.32	0.00
3-7	-5.64	2.55	-2.21	0.03
4-4	-22.37	1.83	-12.21	0.00
4-5	-34.83	1.22	-28.66	0.00
4-6	-35.61	1.84	-19.37	0.00
4-7	-43.31	2.55	-16.97	0.00
5-5	-39.58	2.23	-17.73	0.00
5-6	-39.13	2.23	-17.56	0.00
5-7	-54.63			
6-6	-30.81	4.38	-7.03	0.00
6-7	-33.54	3.12	-10.76	0.00
Rows				
Bottom - Bottom	7.74	1.00	7.77	0.00
Top - Bottom	-18.71			
Top - Top	4.18	0.76	5.51	0.00
Top - Home	0.61	0.57	1.07	0.28
Home - Bottom	0.03	0.63	0.04	0.97
Home - Home	6.15	0.82	7.47	0.00

Table 5.15. Grouping information using Tukey method and 95.0% confidence for the considered factors (cont.).

Rows	N	Mean	Grouping
Bottom-Bottom	448	163.0	A A A B B C
Home-Home	687	161.4	
Top-Top	880	159.4	
Top-Home	1865	155.9	
Home-Bottom	1366	155.3	
Top-Bottom	1458	136.5	
Hand	N	Mean	Grouping
Right	3774	160.9	A B
Left	2930	149.6	
Period	N	Mean	Grouping
Period 1	1670	161.2	A B B B
Period 2	1678	154.3	
Period 3	1678	153.3	
Period 4	1678	152.3	
Means that do not share a letter are significantly different.			

The main effects plots of the factors can be seen in the Figures 5.15, 5.16, 5.17, 5.18 and 5.19. In all of these graphs, the y axis is converted into interkey stroke times by dividing 30000 msec (30 seconds) to the response (number of keystrokes / 30 seconds), so the smaller the y value the faster the digraph typing speed.

Column factor is the most important factor (has the highest explanatory power) that the model has. As seen in Figure 5.15, columns that include index finger (column 1 and column 2) has the least interkey stroke times unless only the index finger is used in the digraph (e.g., column level 1-2). The digraphs that are pressed with the same finger like 1-1, 1-2, 2-2, 3-3, 4-4, 5-5, 5-6, 5-7 have high interkey stroke times. From Figure 5.15, other comparisons for the fingers and columns can be made.

As expected and as seen in the Figure 5.16, there are significant differences between the subjects. However, in the experiments this factor is blocked to eliminate any misleading results.

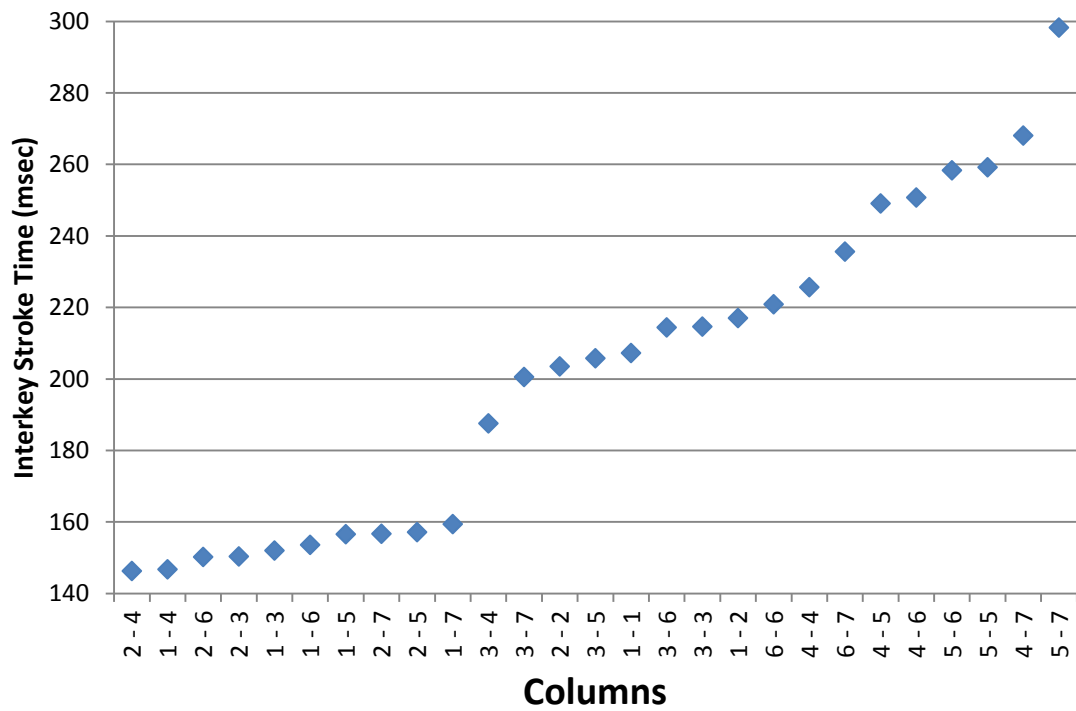


Figure 5.15. Main effect plot for column factor.

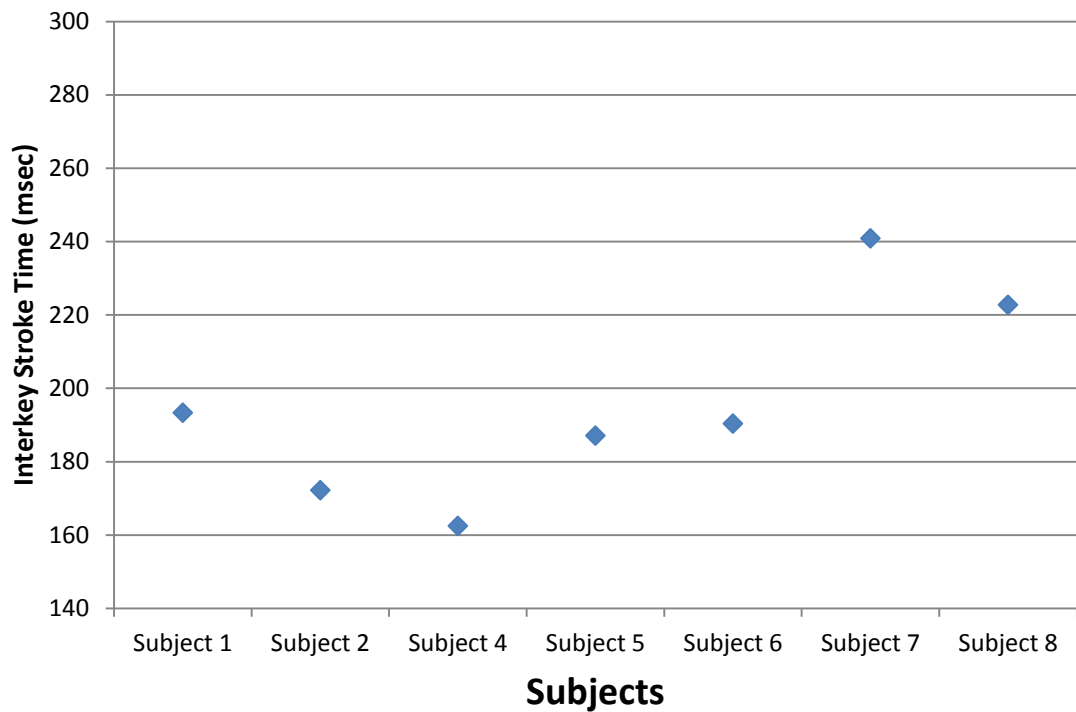


Figure 5.16. Main effect plot for subject factor.

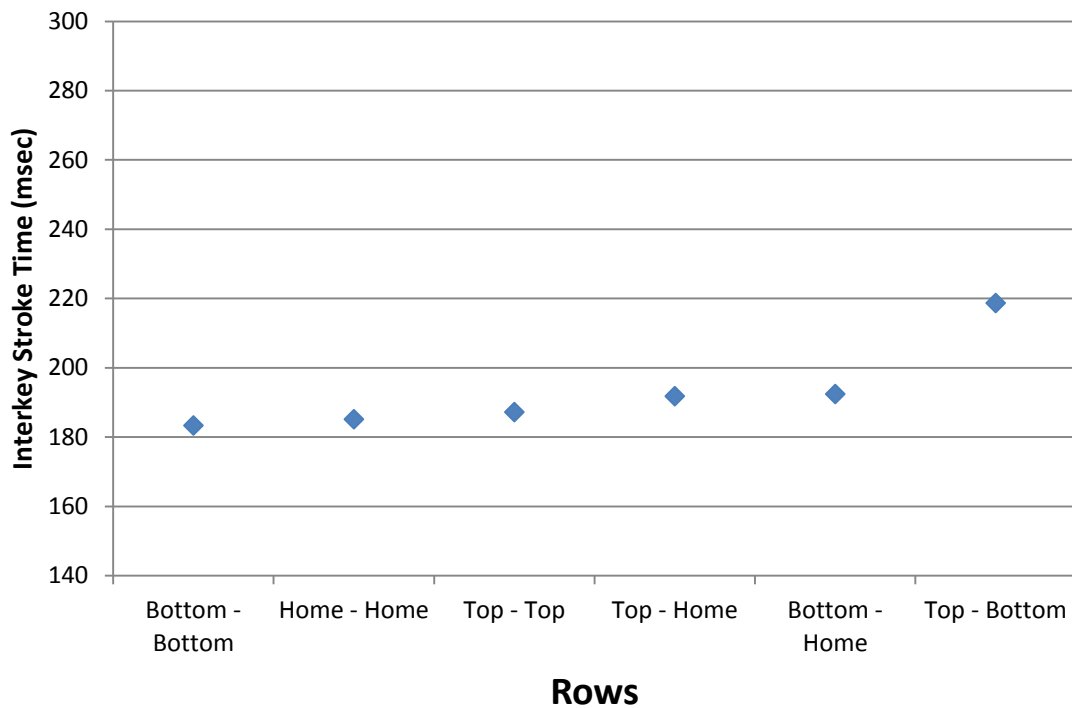


Figure 5.17. Main effect plot for row factor.

When the row factor is analyzed (see Figure 5.17 and Table 5.15), it is seen that it is faster and easier to type if both of the keys in the digraph are on the same row. However, when there is an excessive row hopping between rows like from bottom row to top row (hurdle) or from top row to home row (reach), the interkey stroke times significantly increases to a very high level.

For the hand factor, right hand is significantly faster than left hand (see Figure 5.18 and Table 5.15). Right hand fingers on average types 0.38 taps per second faster than left hand fingers.

For the period factor, there is a significant decrease between first and all other periods (see Figure 5.19 and Table 5.15). However, there is no significant difference between second, third and fourth periods. So it can be concluded that, during experiments subjects start with a high speed, but cannot sustain that speed for a long time. During and after second period, their speed is lowered to a level that they can sustain for a longer time as much as 5 minutes as observed in the pilot studies.

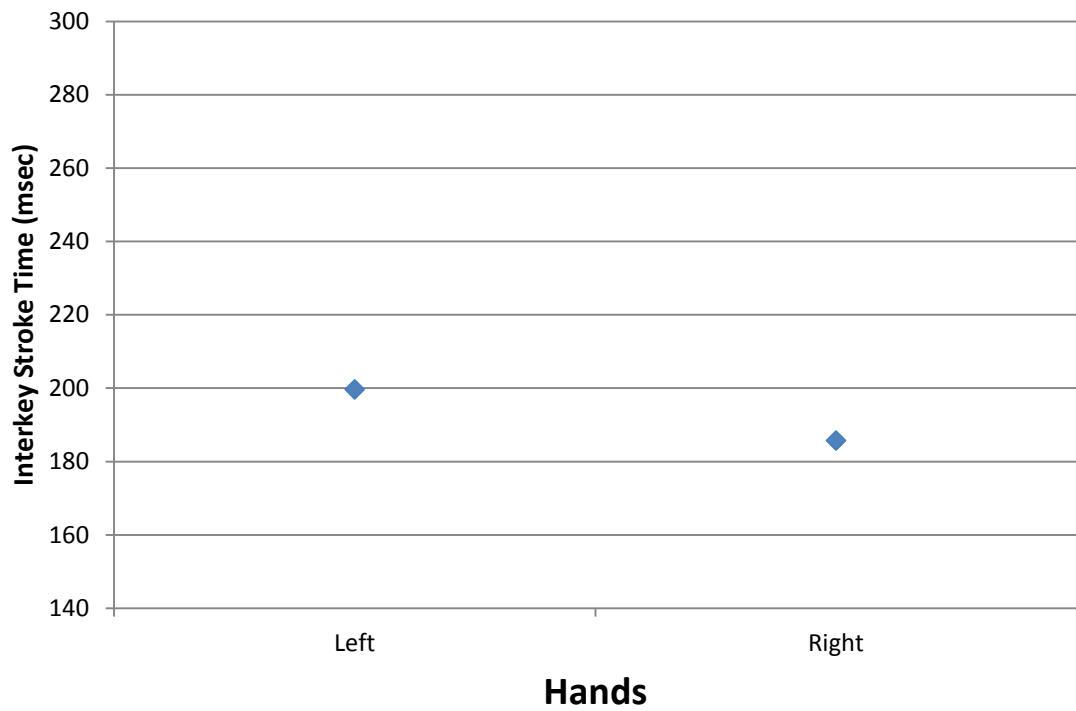


Figure 5.18. Main effect plot for hand factor.

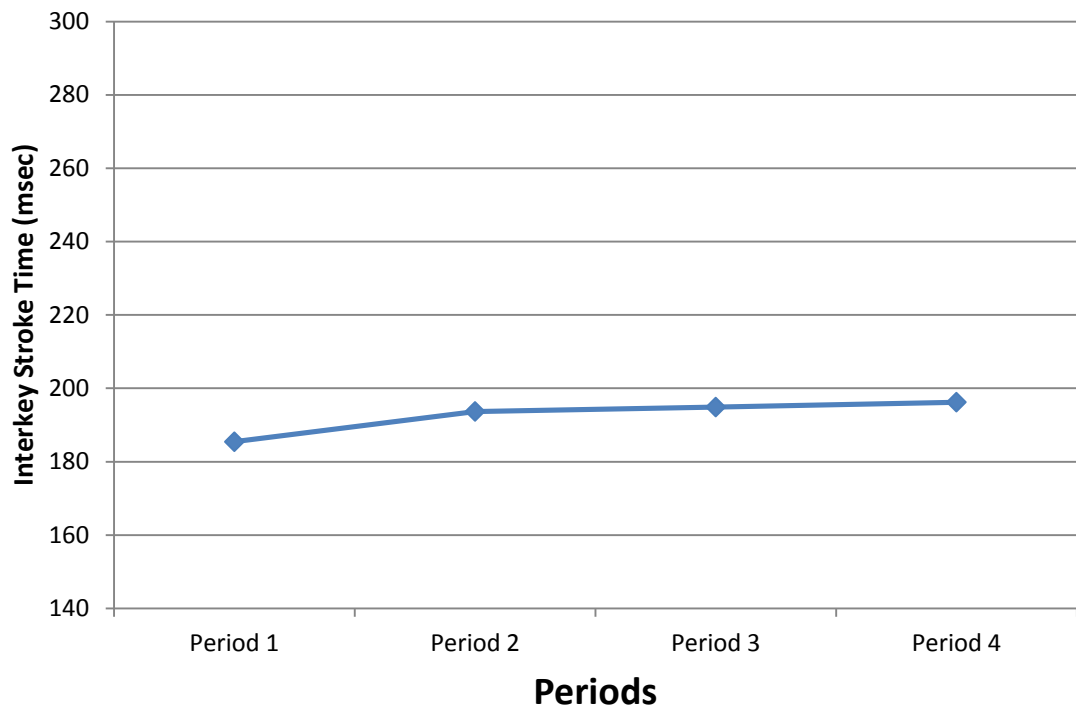


Figure 5.19. Main effect plot for period factor.

5.2.2. Quantification of the Digraph Costs

The main aim in the digraph experiment is quantifying the digraph tapping rates to be used in calculating the digraph costs. To obtain these rates, statistical analyses are done in the statistical package called MiniTab 16. Although we have tested with 8 subjects, the data from one of the female subjects who is left handed were discarded. This is done because of the decision of forming a keyboard layout that is for right handed people.

5.2.2.1. Response Variable and Investigated Independent Variables. The dependent variable (response) is the number of correct keystrokes minus number of errors in periods of 30 seconds (Total # of keystrokes in 30 seconds – 2 * # of errors in 30 seconds). This way number of errors is subtracted two times from the total key presses. This is done, because in general when a typist makes an error, he/she also press backspace to correct his/her error. In other words, each error increases total number of keystrokes by 1. This needs to be subtracted from total; and it takes time to delete the error and that needs to be subtracted as well.

The independent variables are taken as the digraph combinations and periods since subject factor was blocked in the experiment (see Table 5.16).

Table 5.16. Dependent and independent variables and their levels used in the statistical analysis.

	Name	Levels
Dependent variable	Number of correct keystrokes minus number of errors per 30 seconds	
Independent variables	Subjects (block)	
	Digraphs	241 different digraph combination (see Section 12.2.4)
	Periods	1, 2, 3, 4

5.2.2.2. Descriptive Statistics of Response Variable. Descriptive statistics of the digraph data (mean, standard deviation and range) is given in Table 5.17. The mean values are average of 28 values for each digraph since each of 7 subjects typed each digraph in four consecutive 30 seconds periods.

Table 5.17. Descriptive statistics of the 241 digraphs data. Values are given in number of keystrokes per period of 30 seconds (i.e., four consecutive 30 seconds period).

Digraph	$\bar{x}$	s	Min	Max	Digraph	$\bar{x}$	s	Min	Max
20 - 23	228.3	32.1	180	297	19 - 28	210.0	27.5	163	265
20 - 25	223.5	34.0	145	289	21 - 23	209.9	41.4	125	283
20 - 26	223.1	38.9	137	280	19 - 30	209.9	30.6	159	290
20 - 22	222.6	32.2	167	278	21 - 31	209.6	33.8	146	282
18 - 25	222.1	43.4	153	294	8 - 14	208.5	29.4	163	276
18 - 27	220.1	29.5	159	283	17 - 30	208.2	34.4	137	271
20 - 27	219.4	32.4	170	285	21 - 26	208.0	33.6	156	282
16 - 25	219.0	32.8	162	291	4 - 10	207.6	29.6	163	259
18 - 26	218.7	30.7	168	300	20 - 28	207.2	40.8	130	267
18 - 24	218.2	36.3	137	282	17 - 23	207.0	26.5	157	253
21 - 24	217.9	36.1	158	271	7 - 14	206.8	22.5	155	251
19 - 25	216.1	36.6	139	288	6 - 11	206.6	30.2	175	274
16 - 26	216.1	39.6	134	291	19 - 22	206.3	31.4	150	270
21 - 27	214.6	45.4	133	286	17 - 27	205.8	39.2	132	277
19 - 26	213.6	33.9	146	276	17 - 29	205.6	35.6	141	271
20 - 30	213.0	45.6	127	287	18 - 30	205.5	44.6	142	286
18 - 22	211.7	29.4	148	267	9 - 12	205.2	27.7	141	257
18 - 23	211.6	31.0	141	270	6 - 15	205.1	27.9	150	281
20 - 31	211.5	32.0	145	258	16 - 30	204.8	33.9	132	283
17 - 22	211.1	41.7	136	272	8 - 11	204.7	28.1	172	261
16 - 22	210.3	36.9	132	265	7 - 10	204.5	30.7	135	257
7 - 13	204.3	34.8	127	283	1 - 14	187.5	20.7	131	216
20 - 24	204.0	33.6	143	278	21 - 28	186.9	32.2	126	242
5 - 11	203.5	22.7	172	254	1 - 10	186.3	24.3	129	262
21 - 22	203.4	40.3	128	273	3 - 13	186.0	21.1	132	243
9 - 15	203.4	31.4	142	278	8 - 13	185.8	45.3	107	272
4 - 13	203.4	26.8	142	263	19 - 29	184.9	32.6	143	263
8 - 15	203.3	28.7	152	254	7 - 12	184.8	42.9	111	255
17 - 25	203.1	28.8	149	258	3 - 10	184.2	22.8	157	244
19 - 31	203.1	25.9	158	259	20 - 32	184.1	31.9	120	254
5 - 12	202.9	23.3	168	253	1 - 11	183.5	40.7	120	248
16 - 28	202.8	35.7	133	269	3 - 14	183.5	28.3	128	261
17 - 31	202.4	36.1	125	273	2 - 11	183.0	33.4	115	252
5 - 13	201.8	23.2	169	253	4 - 12	182.4	41.0	127	261
19 - 23	201.7	33.5	140	260	2 - 15	182.1	24.5	142	214
8 - 12	201.3	33.5	152	257	2 - 13	181.6	27.5	117	231
4 - 14	200.9	30.4	125	265	2 - 12	180.8	24.5	143	232
4 - 11	200.8	31.6	145	260	18 - 32	180.3	33.1	129	266
18 - 29	200.7	39.6	136	274	9 - 11	179.6	32.1	120	253
21 - 32	200.1	39.4	134	272	7 - 15	177.4	40.0	119	250
20 - 29	199.2	27.1	146	243	24 - 27	174.1	22.0	134	209
5 - 14	199.1	38.8	124	276	4 - 15	173.9	38.7	97	236
5 - 15	198.9	26.3	154	248	18 - 28	172.6	31.7	113	222
16 - 23	198.2	30.2	147	255	21 - 30	172.4	33.0	120	250
19 - 32	197.4	30.2	130	234	23 - 26	170.8	23.3	123	209
6 - 14	197.3	27.2	122	247	22 - 32	168.8	22.6	129	210
17 - 32	197.2	33.6	139	280	4 - 7	167.6	29.3	117	224

Table 5.17. Descriptive statistics of the 241 digraphs data. Values are given in number of keystrokes per period of 30 seconds (i.e., four consecutive 30 seconds period) (cont).

Digraph	$\bar{x}$	s	Min	Max	Digraph	$\bar{x}$	s	Min	Max
17 - 26	196.9	42.5	118	252	5 - 8	166.6	33.1	102	224
17 - 28	196.8	26.0	140	235	23 - 27	166.5	27.9	113	207
21 - 25	196.0	38.4	127	257	23 - 29	166.4	32.8	123	229
7 - 11	195.8	40.0	119	259	5 - 9	165.8	38.3	112	224
1 - 13	195.8	32.2	154	263	6 - 9	165.6	27.5	112	222
16 - 31	195.6	30.4	147	248	24 - 26	165.3	22.4	115	194
2 - 14	195.3	27.2	138	254	1 - 12	164.9	45.7	94	237
16 - 32	193.8	37.6	115	260	16 - 27	163.7	41.2	104	226
6 - 12	193.8	22.9	162	239	6 - 10	163.3	37.6	95	244
8 - 10	193.0	29.4	156	251	19 - 20	162.2	18.8	124	191
3 - 11	191.1	32.4	130	266	24 - 31	162.0	21.5	129	203
2 - 10	190.9	27.7	156	273	22 - 25	161.5	27.0	113	198
21 - 29	190.6	36.6	135	249	23 - 25	161.4	22.9	126	211
3 - 15	190.6	26.3	140	243	17 - 19	160.0	11.2	137	177
3 - 12	190.2	28.2	144	257	22 - 26	159.7	28.9	106	214
18 - 31	190.0	34.9	145	248	17 - 24	159.2	38.1	117	236
9 - 14	189.9	31.3	134	262	20 - 21	158.6	15.4	133	187
5 - 10	189.9	32.0	120	244	18 - 20	157.8	15.9	123	178
16 - 29	189.2	37.6	137	257	5 - 7	156.9	25.6	113	213
19 - 27	189.1	38.1	126	274	23 - 30	156.9	19.1	127	195
6 - 13	188.3	28.5	142	239	3 - 9	156.8	32.9	97	207
16 - 19	155.4	16.1	130	195	11 - 14	132.4	9.3	119	151
4 - 8	155.3	34.8	87	204	25 - 29	132.3	26.5	96	197
2 - 7	155.1	33.8	101	237	30 - 31	131.9	22.8	103	170
18 - 21	153.9	13.2	132	174	1 - 8	131.9	30.6	86	187
1 - 15	152.5	44.8	91	226	22 - 30	131.3	21.6	105	196
17 - 18	152.2	12.9	118	177	4 - 9	131.3	33.6	93	216
17 - 20	151.2	22.1	106	184	26 - 31	131.2	16.4	101	160
3 - 8	151.2	28.8	111	204	7 - 8	130.8	15.0	97	158
23 - 31	150.4	24.7	106	199	12 - 15	130.1	8.2	116	146
16 - 17	150.3	15.3	119	175	11 - 13	129.7	14.5	103	152
22 - 31	149.8	26.0	108	185	28 - 30	129.5	17.1	109	171
23 - 24	149.5	18.3	113	195	3 - 6	129.4	30.1	77	207
1 - 7	149.3	36.0	106	218	28 - 29	128.4	23.5	92	172
18 - 19	147.4	16.2	121	176	3 - 7	127.6	25.8	76	179
22 - 23	147.1	18.7	115	171	8 - 9	127.6	15.2	97	163
2 - 9	146.9	30.4	91	196	26 - 30	127.6	23.2	86	162
22 - 27	146.6	30.3	105	211	2 - 4	127.5	33.0	74	205
22 - 29	146.6	24.8	108	216	2 - 5	127.0	27.8	69	175
2 - 8	146.2	33.5	87	203	25 - 27	127.0	20.5	100	170
19 - 24	145.5	32.1	114	212	26 - 29	127.0	26.7	89	173
26 - 27	145.1	20.6	112	192	9 - 10	126.5	30.4	93	200
25 - 26	145.0	17.6	122	186	29 - 31	126.2	18.4	99	163
23 - 28	144.7	24.9	103	189	10 - 14	126.0	7.5	112	137
22 - 28	144.6	36.5	94	216	3 - 5	124.6	29.3	76	178
24 - 32	144.0	32.5	107	218	30 - 32	124.6	17.9	94	166
23 - 32	142.9	18.0	110	176	4 - 5	124.5	11.9	105	143

Table 5.17. Descriptive statistics of the 241 digraphs data. Values are given in number of keystrokes per period of 30 seconds (i.e., four consecutive 30 seconds period) (cont).

Digraph	$\bar{x}$	s	Min	Max	Digraph	$\bar{x}$	s	Min	Max
16 - 20	142.2	18.0	105	169	10 - 13	121.4	11.7	103	145
6 - 7	142.1	31.0	87	207	11 - 15	120.1	9.8	102	137
19 - 21	142.0	18.8	111	188	25 - 28	119.7	11.8	95	141
6 - 8	140.6	30.5	77	213	26 - 28	119.7	26.5	87	185
17 - 21	139.8	20.8	105	187	13 - 15	119.6	11.7	103	140
16 - 18	139.7	16.6	103	166	25 - 32	119.3	12.8	89	145
13 - 14	137.6	15.4	109	167	5 - 6	119.0	13.4	91	145
11 - 12	137.4	13.1	116	175	1 - 5	118.3	19.4	92	164
1 - 4	135.7	30.6	85	184	9 - 13	116.8	22.9	83	165
16 - 24	135.3	27.7	92	196	10 - 12	116.5	16.8	83	139
24 - 25	135.1	23.3	85	171	12 - 13	116.4	10.4	93	134
31 - 32	134.9	16.2	104	165	7 - 9	115.7	12.9	97	151
10 - 11	134.9	13.6	101	159	29 - 32	115.6	27.0	75	165
24 - 29	134.7	20.9	93	167	27 - 30	115.1	19.4	88	165
14 - 15	134.1	17.8	89	161	1 - 2	114.7	14.7	92	149
16 - 21	134.1	15.2	103	158	1 - 9	114.5	37.8	76	188
22 - 24	133.9	17.5	99	160	2 - 6	114.3	17.7	71	141
12 - 14	133.9	11.9	111	154	24 - 30	113.8	18.5	81	153
25 - 30	133.2	21.5	83	167	24 - 28	113.4	20.3	78	169
27 - 31	132.8	29.9	95	198	2 - 3	112.4	10.2	92	130
29 - 30	132.7	15.6	103	166	26 - 32	111.5	13.8	91	137
28 - 31	111.4	24.3	75	152	28 - 32	104.9	21.4	77	141
10 - 15	110.2	11.4	97	142	4 - 6	103.0	12.9	80	124
27 - 32	109.0	14.7	80	139	1 - 6	93.6	24.5	63	167
25 - 31	108.6	16.6	84	137	1 - 3	84.3	14.9	57	116
3 - 4	105.6	16.8	79	133	27 - 28	82.4	25.1	45	123
27 - 29	105.5	26.9	59	155					

5.2.2.3. Inferential Statistics. Statistical analysis is performed for quantifying the digraph cost scores. Below is the mathematical equation of the used statistical model.

$$y_{ijk} = \mu + \beta_i + \alpha_j + \gamma_k + \varepsilon_{ijk}$$

where

y_{ijk} : the response variable (number of correct keystrokes minus number of errors per 30 seconds)

μ : the overall response mean

β_i : the effect of the i th subject (block factor)

α_j : the effect of the j th period ($j = 1, 2, 3, 4$)

γ_k : the effect of the digraph k ($k = 1-2, 1-3, 1-4, \text{etc.}$)

ε_{ijk} : the usual random error term

The result table for the ANOVA is shown in Table 5.18. The coefficients table can be found in the Appendix B1. Using the coefficients in Appendix B1, digraph penalties of every digraph is calculated. The method that is used is explained in the next section.

Using the results of the experimental study, digraph penalties which are used in the optimization procedure are calculated. The way how these experimental results are converted to the digraph penalties are explained in this section.

Table 5.18. ANOVA results table for the digraph experiment.

Source of variation	Degrees of freedom	Seq SS	Adj MS	F	p
Subject (block)	6	2,499,996	395570	938.47	0.00
Digraph	240	8,222,533	34263	81.29	0.00
Period	3	81,311	27104	64.30	0.00
Error	6321	2,664,333	422		
Total	6570	13,468,172			

S = 20.53 R-Sq = 80.22% R-Sq(adj) = 79.44%

5.2.2.4. Calculating the Digraph Costs for Same Hand Digraphs. First of all, digraph costs for the 241 same hand digraphs are calculated such that the cost is expressed as the average time to press from one key to another in the digraph in milliseconds (msec). So digraph cost of digraph_{ij} is the time lag from key i to key j.

To calculate the digraph costs in such a way, first the coefficients (constant + digraph coefficient) in the Appendix B1 are used to find the main effects of each digraph as the number of key presses for 30 seconds. These coefficients in Appendix B1 are the coefficients of the ANOVA model for digraphs. Then to convert those numbers to interkey stroke times in msec, the following conversion formula is used:

$$\begin{aligned}
 \text{Interkey Stroke Time} &= \left(\frac{\text{Constant} + \text{Digraph coefficient}}{30 \text{ sec}} * \frac{1 \text{ sec}}{1000 \text{ millisec}} \right)^{-1} \\
 &= \frac{\text{Average time (millisec)}}{\text{keypress}}
 \end{aligned}$$

For instance, to calculate the digraph cost of digraph_{20,23}, first the coefficient in Appendix B1 is taken (166 + 62 = 228; 166 is the constant and 62 is the digraph coefficient

for digraph_{20,23}). Then as the equation shows 30000 milliseconds is divided by this number ($30000 / 228 = 131$). 131 milliseconds is the digraph cost of pressing key 20 after key 23 or vice versa. Or it can be assumed that pressing key 20 before or after key 23 requires 131 milliseconds.

The higher the interkey times the harder to press that digraph. This way, costs for the 241 same hand digraphs are calculated.

These 241 same hand digraph costs after the conversion can be found in Appendix B2 for comparison.

As explained in the following section, while calculating the digraph costs for different hands, Salthouse' (1984) study is used. For normalization purposes, we multiply all the digraph penalties in Appendix B2 by 1.016 to move the average from 190 msec to 193 msec. 190 msec is the average of all digraph penalties that are calculated from the experiment and listed in Appendix B2 while 193 msec is the average of these types of digraphs in Salthouse' (1984) study. No multiplication factor is used for same finger doubles since the average of these digraphs in the current study is, by chance, the same as Salthouse' (1984) study which is 168 msec. These final digraph costs as they are used in the optimization can be found in Appendix C.

5.2.2.5. Calculating the Digraph Costs for Different Hand Digraphs. These digraph costs are not directly experimentally determined, however they are estimated from the experiments on same hand digraphs. As explained in the previous section, digraphs costs for the same hand digraphs are calculated. However, there are digraphs that are pressed by different hands. The number of this type of digraphs is 255 which is the multiplication of number of keys in the left hand (15) and the number of keys in the right hand (17). In almost all of the keyboard optimization models, all these 255 digraphs are treated as the same. However, below a new way is suggested to calculate the digraph costs of these digraphs:

First of all, it is assumed that in order to press two keys on different hands, typist should move his/her fingers from the standard key position to the position of the key. This

assumption is true if the typist's replacement span is two or one character. However, as explained in Section 2.4, the replacement span of the professional typists is approximately three characters. Nevertheless, this assumption will provide us a way to approximate different hand digraph penalties which is otherwise hard to quantify.

Digraph costs for these digraphs are calculated using the average costs from the standard positions to the individual keys. For instance, for a digraph from key 4 to key 18 (see Figure 4.1), the digraph costs for digraph 4-5 (key 4 is the key in the digraph, key 5 is the standard position of the associated finger in the left hand) and digraph 18-20 (key 18 is the key in the digraph, key 20 is the standard position of the associated finger in the right hand) are averaged. This average is used as a raw cost for the digraph between 4 and 18 (If the key in one hand is also the standard key in the same hand; then for the digraph cost on one hand, the associated finger tapping rate is used which is collected from the monograph experiment). It is well known that two hand digraphs are faster. This is a well documented fact. Salthouse (1984, see Table 2.2) found that the average interkey time for two hand digraphs is 144 msec while the average interkey time for the same hand digraphs is 193 msec. So in order to get the final cost score, we multiply the raw cost with 0.746 (approximately 144/193). This way, on average, two hand digraphs become faster than same hand digraphs as they should be. The whole conversion can be seen below:

$$Cost\ score = \frac{Cost\ score\ in\ the\ left\ hand + Cost\ score\ in\ the\ right\ hand}{2} * 0.746$$

To continue the given example, let's calculate the digraph cost score for digraph_{4,18}. First, as explained above, the digraph costs which can be found in Appendix C for digraphs_{4,5} and digraphs_{18,20} are averaged ((245 + 188) / 2 = 217). Then this number is multiplied by a factor of 0.746 (217 * 0.746 = 162). 162 milliseconds is the digraph cost of digraph_{4,18}.

The whole digraph cost scores which is the distance matrix in the optimization model can be seen in Appendix C.

5.2.3. Power Analysis

After the experiment, a power analysis is done in order to define the power of the tests that are done for the estimation of the digraph penalties. Standard deviation of our response (number of keystrokes in 30 seconds) between the subjects in a specified digraph is estimated as 27.8. Using this standard deviation, a power curve (Figure 5.20) is generated in MiniTab 16 using a two sample t test. This power curve shows the power in which two digraph can be separated from each other ($H_0: \mu_1 = \mu_2$).

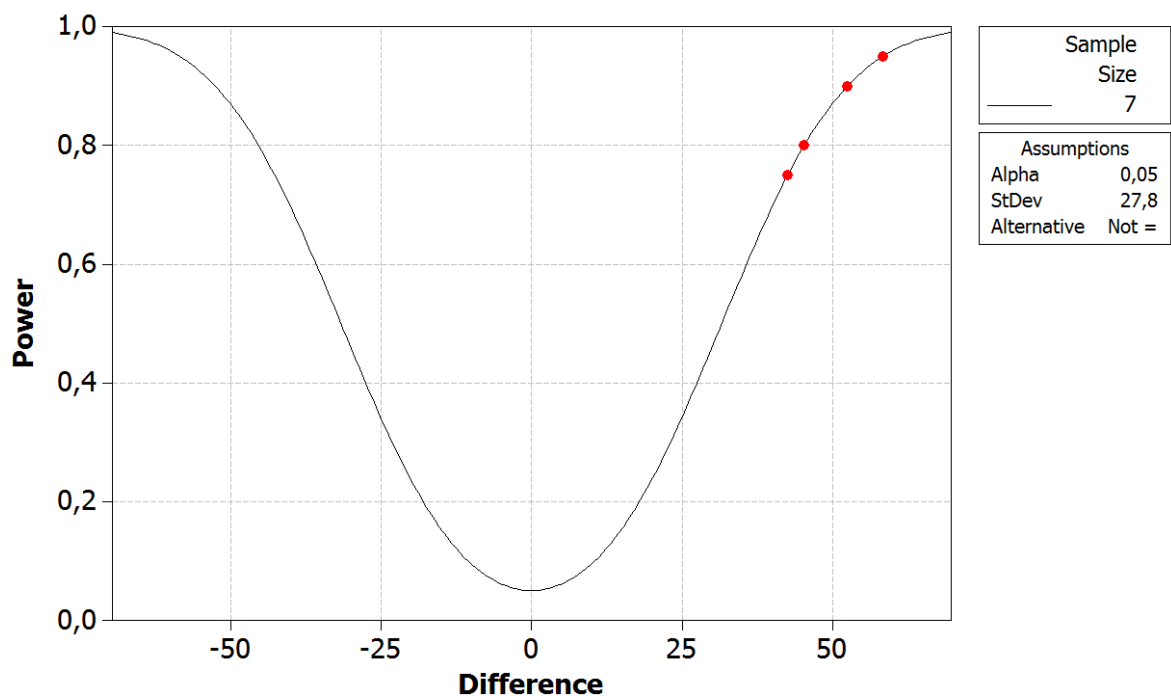


Figure 5.20. Power curve for the experiments to calculate digraph penalties.

As seen from Figure 5.20, with 7 subjects and 75% power, we can detect a difference of 42.6 keystrokes per 30 seconds between two digraphs. In other words, if there is 1.42 keystrokes per second difference between the digraphs in reality, with our experiments we can detect it 75% of the time. This is the power of our digraph experiments.

5.2.4. EMG Results

During all the digraph experiments, surface EMG activity was collected from all subjects' flexor digitorum superficialis (FDS) muscle which is one of the most important

finger flexor muscles. This is done in order to quantify the fatigue for all the digraphs. The details of the procedure are explained in Section 4.6.

The raw EMG data at a sampling rate of 1000 Hz were filtered with two filters: a band pass filter in the range of 20-450 Hz and a band stop filter between 49 and 51 Hz to eliminate the noises in the signal. The band pass filter was the recommendation of the manufacturer (Luca, 2008) while the band filter was put to eliminate the noises from electrical devices whose frequency are 50 Hz in Turkey.

Root mean square (RMS) value of an EMG signal measures the electrical power of the signal. According to most authors, it is the basic way of analyzing the magnitude of the EMG signal. However, in order to compare the RMS values of activities on different days, different subjects, a normalization process is required. In this normalization process, EMG signal is calibrated against a known reference. For many reasons regarding the nature of EMG activity collection procedure, to draw meaningful and quantitative conclusions, one should normalize the RMS values. For the details about EMG activity, one can see the book by Kumar and Mital (1996).

From the filtered EMG data; RMS EMG values are calculated and these values were normalized using the associated day's rest and maximum RMS values. For all of the analysis, the EMGworks software was used. RMS values showed the level of electrical activity in the corresponding muscle and normalized RMS values showed the demand of the job as a percentage of the maximum voluntary contraction (MVC). So when it is higher, it means that more force you need to apply to accomplish that job.

There is another well known analysis called fatigue analysis. It is widely used in determination of localized muscular fatigue in industrial applications. The most well known criterion for fatigue analysis is the shift in median frequency toward lower values. This analysis is done in frequency domain. So first of all in order to convert the EMG signal from time domain to frequency domain, a fast Fourier transformation should be done. And median frequency is the frequency which divides the power spectrum in two parts with equal areas.

When we made fatigue analysis using median frequency criterion, we could not find any significant shift to lower values in two minutes while the subjects typed the same digraph at their maximum speed. However, when the subjects are asked about their fatigue level, they respond with some amount of fatigue varying according to the digraph type, some of them were lower and some of them were higher. Tomatis *et al.* (2009) also found similar results regarding to median frequency in a similar typing experiment.

This can be a result of the nature of the typing job. Typing job is a dynamic job which is performed under low load levels. In the current experiment, average normalized RMS values were about 10%.

The relation between subjectively experienced fatigue and electromyographic signs of fatigue was studied by several authors (Hasson et al, 1989, Öberg *et al.*, 1994). They found that at moderate to high load levels, correlation is quite high while at low contraction levels correlation is poor. Also many authors study the relation between electromyographic signs of fatigue and the load level. They found that at higher load levels, the median frequency is related to load level while at low load levels results are ambiguous (Kumar and Mital, 1996). As a result at loads exceeding approximately 20% of MVC, median frequency provides reliable measures of localized muscular fatigue in isometric contractions at constant effort. However, in dynamic jobs or loads below this threshold, median frequency and other electromyographic fatigue indices become much more unreliable in spite of obvious fatigue reactions (Kumar and Mital, 1996).

So because of the current experimental EMG results and the problem of using median frequency in dynamic and low contraction jobs; although the surface EMG activity is collected in every experiment, it is decided not to use EMG signals and their derivatives in calculating the penalty scores.

5.3. Summary of Experimental Results

Using the results of monograph experimental study, tapping rate capacity of fingers are quantified to be used as parameters with the monograph frequencies of the considered language for defining the monograph penalty of a given keyboard layout. Also, using the

results of digraph experimental study, digraph costs are quantified to be used as parameters with the digraph frequency of the considered language for defining the digraph penalty of a given keyboard layout. Thus, these experimental studies enable us to define the objective function value of the mathematical model for a given keyboard layout during the optimization procedure.

Besides, effects of different factors that affect finger tapping rate (monograph tapping rate) and digraph tapping rate are investigated using the results of monograph and digraph experiments. In monograph experiments, age and the finger factors are found to be the most important factors on finger tapping rate. In digraph experiments, the columns that the digraphs belong are found to be the most important factor.

In addition to these, the use of EMG in the digraph experiment also reveals again the known fact that median frequency and other electromyographic fatigue indices are unreliable when the job is dynamic and requires low load levels like typing. So these indices are not used in the quantification of the parameters.

6. APPLICATION OF THE METHODOLOGY TO TURKISH LANGUAGE

In this chapter, the application of the proposed methodology to Turkish language is explained in details.

6.1. Overview

As explained in Section 3.1 and Section 3.2, one of the objectives of the study is to develop a scientific based, optimal and ergonomic keyboard layout for Turkish language, which is better than the current Turkish F layout. Another objective is comparing the developed layout with Turkish F and Q layouts through validation tests. Towards this end, this chapter covers the application of the proposed methodology and the validation tests in developing an optimal and ergonomic keyboard layout for touch typists of Turkish language.

6.2. Rationale and Objectives

The existing F keyboard layout for Turkish language is lacking in terms of ergonomics criteria and in consideration of the complete characteristics of Turkish language as indicated in Section 2.6. The Turkish F layout is designed only for writing faster according to the letter frequencies in the Turkish dictionaries of 1950's. The drawbacks with this layout can be listed as follows: (i) the only design objective of this layout was fast typing (ergonomics criteria is not considered), (ii) letter frequencies are calculated only from dictionaries of 1950's, (iii) the words used in Turkish language changed over the past 50 years, (iv) it is not scientifically based (i.e., there is no scientific methodology followed in its development).

Therefore; it is a matter of efficiency, health and comfort needs to develop a scientific based, optimal keyboard layout for Turkish language while considering ergonomics criteria to reduce typing induced health problems and improve typing performance and comfort among typists.

Besides, none of the studies which used optimization techniques carried out validation studies which would prove that their layouts were better than the existing layouts.

In the application of the proposed methodology to Turkish language, an optimal and ergonomic keyboard layout is formed and this new layout is compared with the existing Turkish F and Q layouts in validation tests. These validation tests also validate the proposed methodology while trying to validate the new layout since this new layout is a product of the proposed methodology.

6.3. Optimization Procedure

For the application, the code for optimizing the model is created in MatLab R2010b. This code is an implementation of the NSGA II algorithm that is described in Section 4.3 to the proposed mathematical model. The details of this implementation are explained below.

6.3.1. Individuals (Chromosomes)

Individuals are the feasible solutions (in our case, potential keyboard layouts) that are defined in permutations of 32. In these permutations, the order of the keys shows the location of the keys. For instance, Q layout is an individual and has a permutation of 30-1-29-32-22-31-6-5-3-21-7-27-24-8-2-28-10-17-25-13-16-11-14-19-18-15-4-20-23-9-12-26 which means that letter 30 (q) is in the 1st location, letter 1 (a) is in the second location, so on (for the numbering of the locations in conventional keyboard, see Figure 4.1). Each of these numbers inside the chromosome (individual) is called as a gene.

Here, for the coding purposes, each letter in Turkish alphabet is assigned a number as shown in Table 6.1. This is done because the software can handle numeric characters easier.

Table 6.1. Ordering of the keys according to Turkish alphabet and the current study.

Key	Order		Key	Order
a	1		n	17
b	2		o	18
c	3		ö	19
ç	4		p	20
d	5		r	21
e	6		s	22
f	7		ş	23
g	8		t	24
ğ	9		u	25
h	10		ü	26
ı	11		v	27
i	12		y	28
j	13		z	29
k	14		q	30
l	15		x	31
m	16		w	32

6.3.2. Population Size and Creation Function

The population size is defined as 15 times (default value of the MatLab module) the number of variables (32 keys and characters) which is 480. So each population in the evaluation has 480 individuals (solutions or layouts).

To create the first population, random individuals are used except the four individuals. Two of these four individuals are Turkish Q layout and Turkish F layout which is the best layout in Turkish until now. The other two are the best solutions obtained when the proposed model is run twice, each time with only one objective function (i.e., the solution obtained by solving the optimization model only with monograph penalty, and the solution obtained by solving the optimization model only with digraph penalty).

For the monograph objective function, a linear model is written and solved to the optimality in an optimization program called XPress MP. The optimal solution value that is obtained from Xpress MP and used is 0.11%. This value indicates that there is at least one solution that the sum of absolute differences between the actual loads and the desired loads is nearly zero.

As explained earlier, when just digraph penalty is considered, the model reduces to a QAP. The lower bound of the QAP model is 136.01 msec. This lower bound is calculated by multiplying the maximum flows (digraph frequencies of letters in Turkish) with the minimum distances (digraph costs of keys). Below, how this lower bound is calculated is shown.

No	Frequencies of Digraphs (listed in descending order)	Digraph Costs of keys (listed in ascending order)	Multiplication of frequencies of digraphs by digraph costs of keys
1	3.26 %	119 msec	3.88 msec
2	2.80 %	119 msec	3.33 msec
...	...	...	...
1024	0.00 %	364 msec	0 msec
sum of all the multiplications			136.13 msec

As for the best solution, it is obtained from the code supplied by Misevicius (2004) for the solution of QAP. His algorithm is proven to solve QAP models very effectively and efficiently. The best solution that is found by Misevicius' algorithm for the digraph penalty is 141.37 msec. The lower bounds and the objective function values of the four individuals that are put in the initial population are shown in Table 6.2.

Table 6.2. Lower bounds for the objectives and the objective function values of Q, F, and best solutions for each objective.

	Digraph Penalty (msec)	Monograph Penalty (%)
F Layout	149	40
Qwerty Layout	170	31
Best Digraph Layout	141	31
Best Monograph Layout	175	0
Lower Bound	136	0

The MatLab code for the creation function is in Appendix D1.

6.3.3. Selection and Crossover Rate

The selection function of the NSGA II algorithm is used. Thus, crowded comparison operator which is described in Section 4.3 is used as the selection function in the

tournaments. The tournament size used in the application is 2 which is the same case in most of the applications.

Crossover rate shows which portion of the offspring population reproduce using crossover operators. The remaining portion reproduces using mutation operators. We use two crossover ratios in the runs; these ratios are 0.5 and 0.8. With these two ratios, in different runs different proportions of individuals are formed using different operators.

6.3.4. Mutation

Three different mutation operators are used in the program. These are insertion, inversion and swap mutation operators. The program applies these operators in the same order to the selected chromosomes (individuals). So one third of the chromosomes selected for the mutation are mutated with each mutation operator.

For the sake of simplicity, the examples in every mutation operator are shown using a chromosome of 9 genes, not 32 as in the application.

Inversion: Inversion operator reverses the sub-string between two randomly selected points in the path. For example: (1 2 |3 4 5 6 7| 8 9) is changed into (1 2 |7 6 5 4 3| 8 9).

Insertion: Insertion operator takes one of the genes and inserts it into a random position ahead. For example: (1 2 |3| 4 5 6| 7 8 9) is changed into (1 2 4 5 6 |3| 7 8 9).

Swap: Swap operator swaps two random genes along the chromosome. For example: (1 |2| 3 4 5 |6| 7 8 9) is changed into (1 |6| 3 4 5 |2| 7 8 9).

The MatLab code for the mutation is in Appendix D2.

6.3.5. Crossover

There are several crossover operators for permutation type chromosomes (individuals). Some of them are: Partially-matched crossover (PMX), cycle crossover

(CX), order crossover operator (OX), one point crossover (OPX), position-based crossover operator (POS), voting recombination crossover operator (VR), alternating-position crossover operator (AP).

In the application, order crossover operator (OX) and one point crossover (OPX) are used since they are widely used in most applications and easy to compute. The MatLab code for the crossover operation is in Appendix D3.

Again for the sake of simplicity, the examples in every crossover operator are shown using a chromosome of 9 genes, not 32 as in the application.

6.3.5.1. OX operator. A portion of one parent is mapped to a portion of the other parent. From the replaced portion on, the rest is filled up by the remaining genes, where already present genes are omitted and the order is preserved. Here is an example:

Parent1 = (1 2 3 | 4 5 6 7 | 8 9)

Parent2 = (4 5 2 | 1 8 7 6 | 9 3)

First, the segments between cut points are copied into the offspring:

Offspring = (x x x | 4 5 6 7 | x x)

Next, starting from the second cut point of one parent, the genes from the other parent are copied in the same order. The sequence of the genes in the second parent is 9 – 3 – 4 – 5 – 2 – 1 – 8 – 7 – 6. After removal of genes from the first offspring we get 9 – 3 – 2 – 1 – 8. This sequence is placed in the offspring:

Offspring = (2 1 8 4 5 6 7 9 3).

6.3.5.2. OPX operator. A crossing point (site) is chosen randomly between 1 and n–1 in one of the parents. As a result, a child chromosome is obtained, containing information partially determined by each of parent chromosomes. Again, it must be considered to preserve the solution feasibility. Below is an example:

Parent 1 = (1 2 3 4 5| 6 7 8 9)

Parent 2 = (4 5 2 1 8 7 6 9 3)

First of all, the part from the first parent is copied to the child.

Child = (1 2 3 4 5|x x x x)

Then after removing the current genes from the child, the remaining parts of the child are filled with the gene order of the second parent (8-7-6-9).

Child = (1 2 3 4 5|8 7 6 9)

6.3.6. Fitness Function

Fitness (objective) function that is described in details in Section 4.2 is coded. For calculating the fitness of a solution, we need digraph costs for every digraph, digraph frequencies, monograph frequencies and desired target finger loads. The calculation of the digraph costs that form the distance matrix is explained in Section 5.2 and the values of digraph costs can be found in Appendix C.

For the monograph and digraph frequency calculations in Turkish language, Turkish National Corpus (Aksan et. al, 2012) is taken as the reference. Using a computer program, all the monograph and digraph frequencies in Turkish National Corpus (TNC) are counted. These frequency data can be found in Appendix E1, E2 and E3. Appendix E1 includes the monograph frequencies in TNC. Appendix E2 shows the digraph frequencies in TNC including “space” characters. This matrix is asymmetric which means that two digraphs which have the same two letters (like ak and ka) have different frequency values. In Appendix E3, there is a modified digraph frequency matrix that was generated from the matrix in Appendix E2. In this matrix, spaces and all the double letters like aa, bb, etc are ignored. And a symmetric matrix is created by summing all the digraphs which have the same two letters like ak and ka. This is done since the digraph costs that are calculated from the experiments do not consider the hit direction as explained in Section 4.6, i.e., $\text{digraph}_{i,j}$ and $\text{digraph}_{j,i}$ has the same digraph cost. Besides, using the symmetric digraph

frequency matrix in Appendix E3, calculations of the fitness are done quickly since flow and distance multiplications are only done once for each digraph. Also the values in this matrix are taken after dividing them with 100. So when we multiply the flow and distances together, the digraph penalty score is the approximated average time in milliseconds for one keystroke in that keyboard layout.

For the optimal finger load, monograph experimental study results are used which is explained in Section 5.1. The optimal finger loads that are calculated are shown in Table 5.10.

The code for the calculation of the fitness function can be found in Appendix D4.

6.3.7. Main Loop

For the main loop, genetic algorithm standard procedure is used. This code is generated using the MatLab optimization toolbox. For stopping criteria, default settings in the MatLab toolbox are used. The only parameter changed is the Pareto front population fraction which defines the maximum portion of the next population that will be formed by Pareto optimal solutions. A lower value increases the diversity while a higher value increases the convergence speed. The program is run with two settings, with 0.35 and 1.

The MatLab code for the main loop is in Appendix D5.

6.4. Optimization Results

Optimization procedure was run twice for 29 and 32 characters. The results of these optimization runs are explained in this section.

6.4.1. Runs with 32 Characters

In the runs, crossover rate (CR) of 0.5 and 0.8; and Pareto front population fraction (PR) of 0.35 and 1 are used. So there are 4 settings. 6 replications are run with each of these settings. In each run, a Pareto front is created. After 24 runs are finished, all Pareto

optimal solutions from each run are gathered together and a single total Pareto front was created. This total Pareto front is shown in Figure 6.1.

In the total Pareto front, there are 91 Pareto optimal solutions. And two of these solutions are the starting best solutions that are obtained for single objectives. These are at the furthestmost right and top regions of the Pareto front.

Previously, the lower bound for the digraph penalty is calculated as 136 msec and the digraph penalty for F layout is calculated as 149 msec and the digraph penalty for Turkish Q layout which is a random keyboard layout according to Turkish language is calculated as 170 msec (see Table 6.2). And as seen from Figure 6.1, the Pareto front lies approximately between 141 and 146 msec for the digraph score. These scores can be thought as the approximated average time in milliseconds for one keystroke (average interkey stroke time) in the associated keyboard layout.

It is important to note that in most of the solutions which have low digraph penalty scores in the Pareto front; all the vowels are in the left side of the keyboard. The reason for this can be increasing the typing speed since digraphs which are typed by alternating hands are faster and most of the digraphs in Turkish language contain one vowel and one consonant. And another important note about the solutions is that; in most of them, characters that are not used in Turkish alphabet like q, x, w and j are located in keys 1, 3, 4 and 6 (see Figure 4.1). These keys are the keys that are located at the top and bottom rows of the keyboard and pressed by left little and left ring fingers.

When the situation for the monograph score is analyzed, from Table 6.2 again it is seen that the lower bound for this score is 0.11% which is very close to zero. The monograph scores for the F layout and Q layout is calculated before as 40% and 31% respectively (see Table 6.2). In the Pareto front monograph penalties lie mostly between 0% and 30%. The spread of monograph penalties is wider than those of digraph penalties as can be seen in Figure 6.1.

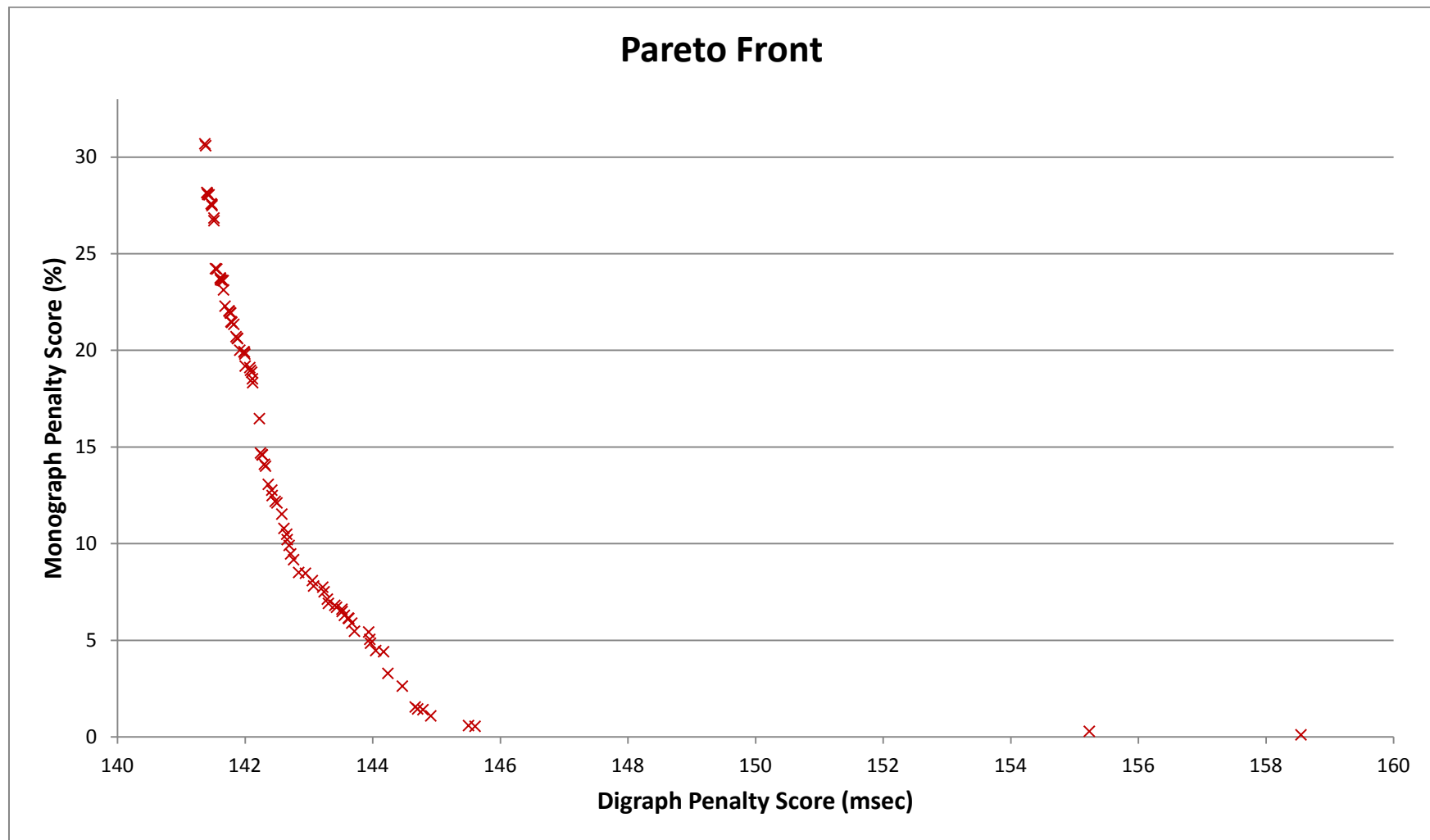


Figure 6.1. Total Pareto front that is formed by 24 runs of NSGA II algorithm with different crossover rates and Pareto front population fractions.

6.4.2. Runs with 29 Characters

In Turkish alphabet, there are 29 characters and q, x and w letters are never used. So after finishing the normal runs with all the 32 letters, different runs are done with just 29 letters. During these runs; q, x and w are restricted to the keys 30, 31 and 32 (see Figure 4.1). These keys are the locations that are far to the right side of the keyboard and pressed by right little finger. Turkish F layout also places q, x and w to these locations.

Again in these runs, crossover rate (CR) of 0.5 and 0.8; and Pareto front population fraction (PR) of 0.35 and 1 are used. 6 replications are run with each of these settings. In each run, a Pareto front was created. After 24 runs were finished, all Pareto optimal solutions from each run are gathered together and a single total Pareto front is created. This total Pareto front for the restricted model with only 29 characters is shown in Figure 6.2 with the total Pareto front for the unrestricted model.

In the total Pareto front of the restricted run with q, x and w in fixed positions, there are 61 Pareto optimal solutions. Since this is a restricted model, as can be seen from Figure 6.2, Pareto front of the restricted model is worse than the unrestricted model. In the restricted model's Pareto front, the best digraph score is 142 msec.

It is important to note that in most of the solutions which have low digraph penalty scores in this Pareto front; all the vowels are in the right side of the keyboard unlike the unrestricted model (in the unrestricted model, in most of the solutions all the vowels are on the left side). Taking all the vowels to the right by the optimization procedure can be the result of typing faster and balancing the loads of the fingers at the same time. Since q, x and w are assigned to the right side, optimization procedure may assign all the vowels to the right hand. Because q, x and w have no frequencies in Turkish language while vowels have high frequencies (see Appendix E1).

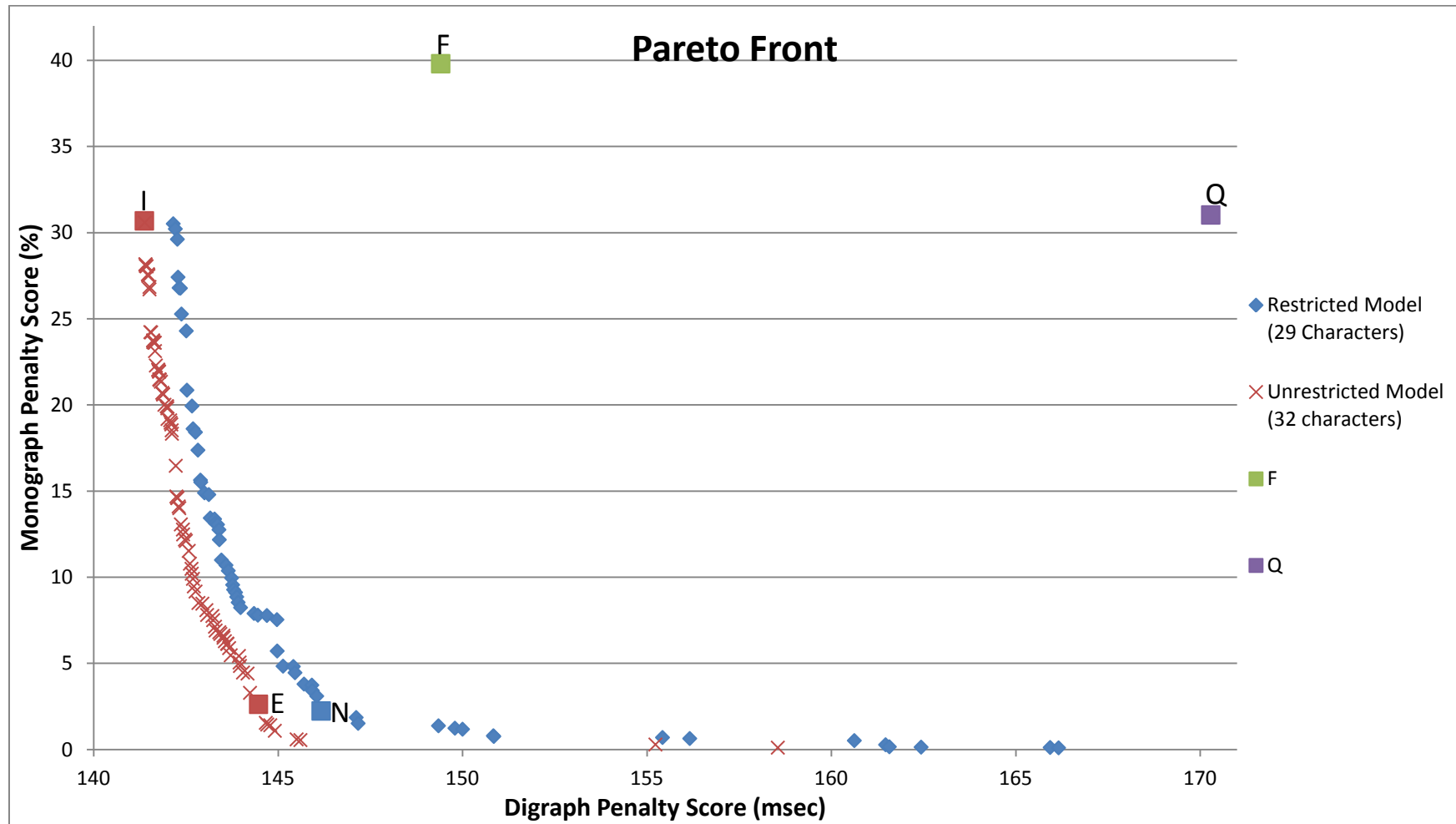


Figure 6.2. Comparison of two Pareto fronts of the restricted model (29 characters) and unrestricted model (32 characters) that are formed by 24 runs of NSGA II algorithm with different crossover rates and Pareto front population fractions. Although not in Pareto fronts, for the purpose of comparison, location of F and Q layouts are also shown.

6.5. Selection of Near Optimal Keyboard Layouts for Further Analysis

In the unrestricted runs there are 91 Pareto optimal solutions and in the restricted runs there are 61 Pareto optimal solutions. However, in order to carry on the validation study, some of these should be selected as candidate solutions and be compared with F and Q layouts. It is not feasible and also not necessary to perform validation tests on all these 152 (91 + 61) keyboard layouts. In addition, due to the QAP structure, most of the Pareto optimal solutions that are close to each other in the Pareto front are similar to each other.

For the purpose, it is decided to make tests on 5 keyboard layouts. Two of these layouts are the Turkish F and Q layouts while 3 others are selected from the two Pareto fronts as the candidate layouts. The first one that is selected is the one that has the lowest (best) digraph penalty score, but has a high monograph penalty score. So this layout is the one that should be the fastest. This layout is called as I layout and shown in Figure 6.3. Its location in the Pareto front can be seen in Figure 6.2. The candidate keyboard layouts including I layout is named according to the first key in the home row.

+ *	! 1	" 2	^ 3	\$ 4	% 5	& 6	' 7	(8	) 9	= 0	? /	- .	← Backspace
Tab ↔	X	P	Ü	O	J	C	S	M	Ş	V	Ğ	F	↵ Enter
Caps Lock ⬆	I	İ	E	A	Ç	T	L	R	N	K	H	; ,	↵ Enter
Shift ⬆	> <	Q	W	Ö	U	G	D	B	Y	Z	: .	Shift ⬆	
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl

Figure 6.3. I layout which has the lowest digraph penalty score.

The other two layouts are selected from the two Pareto fronts, one from each. For selecting these layouts, it is decided to use the area which has a monograph penalty score of less than 5% and a digraph score of less than 148 msec. This area of the Pareto fronts can be seen in Figure 6.4.

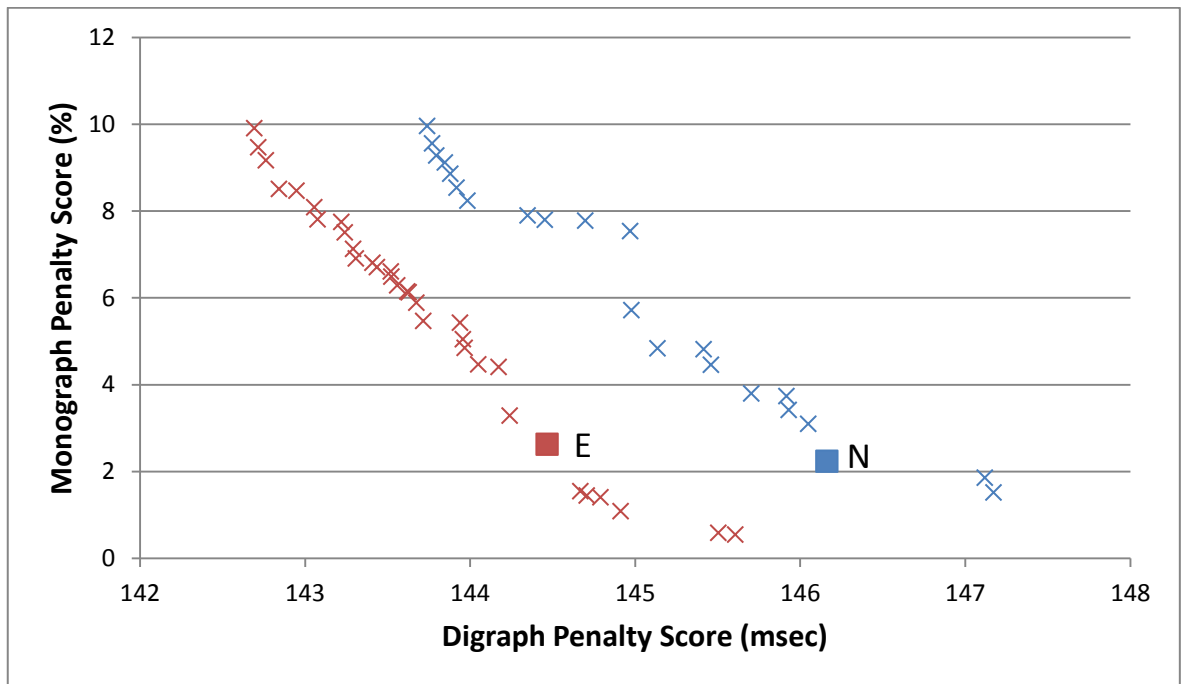


Figure 6.4. Zoomed in region of the Pareto fronts. Solutions have a monograph penalty less than 10% and a digraph penalty less than 148 msec.

After zooming in the region where the monograph penalty is less than 10% and digraph penalty is less than 148 msec, a choice should be made. So all the layouts in this region are investigated and after this investigation it is seen that most of the keyboard layouts which are on the same front in this region have similar layouts (letter assignments). This is because of the structure of the QAP model. Although most of the solutions have similar layouts and little difference between them, one of them should be selected subjectively from each front. So after investigation of all the layouts and the Dvorak's criteria which will be explained in Section 6.6.3, E layout is selected from the unrestricted Pareto front while N layout is selected from the restricted Pareto front.

The location of the layouts that are selected from the unrestricted (Figure 6.1) and restricted Pareto fronts (Figure 6.2) are shown in the Figure 6.4 and the layouts are shown in Figure 6.5 and Figure 6.6. The one from the unrestricted model is called as E layout (Figure 6.5) and the one that is selected from the restricted model is called as N layout (Figure 6.6). For the layouts of other solutions around E and N layouts in the Pareto front (see Figure 6.4), you can check Appendix F. Besides, Appendix G lists all the solutions that is on the restricted or unrestricted Pareto fronts.

+ *	! 1	" 2	^ 3	\$ 4	% 5	& 6	' 7	(8	) 9	= 0	? /	- _	← Backspace
Tab ↔	Q	J	Ü	O	F	C	T	M	K	B	S	P	↵ Enter
Caps Lock ↑	E	A	İ	İ	G	Ğ	L	N	R	D	V	; ,	↵ Enter
Shift ↑	> <	X	W	Ö	U	H	Z	Ç	Y	Ş	:	↵ Shift	
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl

Figure 6.5. E layout which is selected from the Pareto front that is obtained with unrestricted runs.

+ *	! 1	" 2	^ 3	\$ 4	% 5	& 6	' 7	(8	) 9	= 0	? /	- _	← Backspace
Tab ↔	Ş	H	K	Ğ	F	V	C	Ü	Ö	U	Q	X	↵ Enter
Caps Lock ↑	N	R	L	D	T	S	I	A	E	İ	W	; ,	↵ Enter
Shift ↑	> <	Ç	B	Z	Y	P	M	G	J	O	:	↵ Shift	
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl

Figure 6.6. N layout which is selected from the Pareto front that is obtained with restricted runs.

6.6. Validation Studies

Validation tests are carried out for validating the candidate layouts and the proposed methodology. The details of these tests are explained in this section.

6.6.1. Overview

One of the objectives of the study is to compare the developed layouts (E, N and I) within themselves and with the existing F and Q layouts in order to determine the best layout. For this aim, one evaluation and two experimental studies are performed. Evaluation study is performed using existing Dvorak *et al.*'s criteria (1936) and experimental studies are performed using tendon travel and typing speed as criteria. The results of the validation studies would also validate the proposed methodology.

Two different methods - typing speed and tendon travel – are used as the criteria for the validation tests. These methods are totally different than the methods that are used in the previous experiments. The details of the validation tests are explained below.

6.6.2. Rationale and Objectives

None of the keyboard layout optimization methods in the literature carried out validation studies which would prove that their layouts were better than the existing layouts. However, without validation tests, one cannot be sure of the superiority of a given keyboard layout even though the optimization results suggest so. In addition, the proposed methodology by the current study is new and the validity of the results would also validate the proposed methodology. Furthermore, the best of the three selected candidate layouts needs to be determined to obtain the optimal and ergonomic keyboard layout for Turkish language.

6.6.3. Evaluation of the Layouts by Dvorak's Criteria

In this section, the layouts are evaluated using Dvorak's criteria. In his book, Dvorak *et al.* (1936) defined some criteria to evaluate a keyboard layout while he criticized the Q layout. Here, these criteria are investigated and all the Pareto optimal solutions are compared with F and Q layouts using the Dvorak's criteria. This way the procedure is tested using the well known optimal keyboard layout design criteria. It is a fair test, since the criteria detailed below are never directly used in the optimization procedure of the proposed methodology.

Dvorak's eleven criteria of keyboard design can be listed as below:

- (i) Deviation from the balance of hand and finger loads: This criterion is the same as our monograph penalty score. According to this criterion, the loads on each finger should be balanced according to the finger capacities. While balancing these loads, Dvorak used the data from Riemer's (1929) study. These loads that are used by Dvorak can be seen in Table 5.10. For the evaluations for this criterion, finger tapping rate

capacity values of Dvorak are used instead of the quantified finger tapping rate capacities of the current study (see Table 5.10). This way the comparison is fairer.

- (ii) Percentage of tapping with the same fingers: The percentage of the digraphs that are tapped with the same finger should be as small as possible since tapping with the same finger reduces the speed. This can be calculated by summing the frequencies of the digraphs that are tapped with the same finger.
- (iii) Percentage of tapping that includes top row: Tapping should be mainly done in the home row which is fastest. Tapping in the top or bottom rows are slower. So the percentage of digraphs that includes one or both letters in the top row should be as small as possible.
- (iv) Percentage of tapping that includes bottom row: Tapping should be mainly done in the home row which is fastest. Tapping in the top or bottom rows are slower. So the percentage of digraphs that includes one or both letters in the bottom row should be as small as possible.
- (v) Percentage of tapping in the home row: Tapping should be mainly done in the home row which is fastest. Tapping in the top or bottom rows are slower. So the percentage of digraphs that both of the letters are pressed in the home row should be as large as possible.
- (vi) Percentage of tapping by alternating hands: Tapping with alternating hands such as one right and one left hand tapping consecutively is fastest. So the percentage of digraphs that are tapped with left and right hand should be as large as possible.
- (vii) Percentage of hurdles with the same finger: Moving from top to bottom rows or vice versa (hurdles) is slow. If hurdle takes place in the same finger, this is slower than the others. So percentage of the hurdles with the same finger should be as small as possible.
- (viii) Percentage of hurdles with adjacent fingers: Moving from top to bottom rows or vice versa (hurdles) is slow. Although it is better to have the hurdle in adjacent fingers than the same finger, this is still slow. So percentage of the hurdles with adjacent fingers should be as small as possible.
- (ix) Percentage of hurdles with remote fingers: Moving from top to bottom rows or vice versa (hurdles) is slow. Although it is better to have the hurdle in remote fingers than in adjacent fingers or the same finger, this is still slow. So percentage of the hurdles with remote fingers should be as small as possible.

- (x) Percentage of reach with the same finger: Moving one row up or down (reach) is slower than tapping in the same row. Although reach is faster and better than hurdles, it is still not desired. So the percentage of reach with the same finger should be as small as possible.
- (xi) Percentage of reach with adjacent fingers: Moving one row up or down (reach) is slower than tapping in the same row. Although reach with adjacent fingers is faster and better than reach with the same finger, it is still not desired. So the percentage of reach with adjacent fingers should be as small as possible.

All of the Pareto optimal solutions from unrestricted model together with F and Q layouts are evaluated according to Dvorak's criteria that are explained above. In these evaluations, the parameters that are used in optimization procedure are not used except the monograph and digraph frequencies in Turkish National Corpus (Aksan *et al.*, 2012). However, to calculate the percentage of tapping in every criterion according to Turkish language, the monograph and digraph frequencies that are calculated from Turkish National Corpus (Aksan *et al.*, 2012) are used.

The results of the evaluations for the 91 Pareto optimal solutions of the unrestricted runs are given in Table 6.3.

The 61 Pareto optimal solutions from the restricted runs are also evaluated according to Dvorak's criteria. The comparisons are in Table 6.4.

When the comparisons are analyzed, it can be seen that for Turkish language the developed keyboard layouts are far better than F and Q layouts in most of the criteria. For instance, percentage of tapping with the same finger is 6% in F layout and 10% in Q layout; however, in most of the developed layouts, it is below 1%. Percentage of tapping in the home row is 31% in F layout and 19% in Q layout, in most of the developed layouts it is more than 40%. Percentage of tapping by alternating hands is 80% in F layout and 49% in Q layout, in most of the developed layouts it is greater than 85%. You can check the other criteria from Table 6.3 and 6.4.

Table 6.3. Comparisons of the Pareto optimal solutions with F and Q layout according to the criteria defined by Dvorak *et al.* (1936) for the unrestricted runs. Criteria marked with an * indicate the larger the better while all the others indicate the smaller the better.

Keyboard Layout	Deviation from the balance of hand and finger loads (%)	Percentage of tapping with the same fingers	Percentage of tapping that includes top row	Percentage of tapping that includes bottom row	*Percentage of tapping in the home row	*Percentage of tapping by alternating hands	Percentage of hurdles with the same finger	Percentage of hurdles with adjacent fingers	Percentage of hurdles with remote fingers	Percentage of reach with the same finger	Percentage of reach with adjacent fingers
F	38.01	6.18	60.11	21.35	31.12	80.38	1.10	0.34	0.07	4.28	4.38
Q	29.73	9.68	75.32	36.57	18.84	48.62	2.60	4.53	2.20	5.69	5.61
I	27.33	2.37	34.24	33.48	41.75	84.93	0.03	0.50	0.14	1.67	3.26
2	27.23	2.33	34.13	33.59	41.75	84.93	0.03	0.50	0.17	1.66	3.28
3	8.79	2.00	37.24	32.98	39.50	85.39	0.05	0.24	0.14	1.63	3.54
4	24.35	2.29	36.51	31.45	41.24	85.15	0.07	0.24	0.10	1.91	3.16
5	19.93	2.36	37.10	34.67	38.41	85.15	0.40	0.23	0.20	1.79	3.36
6	23.63	2.30	36.51	31.45	41.24	85.15	0.07	0.27	0.07	1.92	2.91
7	19.21	2.37	36.71	31.25	41.24	85.15	0.08	0.24	0.13	1.99	3.02
8	19.13	2.13	36.09	31.87	41.24	85.15	0.06	0.24	0.14	1.77	3.27
9	18.17	2.44	39.62	31.14	39.26	85.15	0.07	0.22	0.14	2.12	3.50
10	18.05	2.12	38.59	31.98	39.57	85.15	0.12	0.06	0.28	1.75	2.99
11	17.43	2.22	38.89	31.87	39.26	85.15	0.05	0.25	0.15	1.92	3.48
12	17.35	2.21	38.89	31.87	39.26	85.15	0.05	0.25	0.15	1.91	3.50
13	16.71	2.46	39.51	31.25	39.26	85.15	0.07	0.24	0.15	2.14	2.94
14	16.61	2.45	41.40	29.36	39.26	85.15	0.07	0.21	0.17	2.13	2.96
15	5.21	2.05	39.55	30.72	39.62	85.15	0.14	0.23	0.22	1.67	2.52
16	24.23	2.72	33.82	36.70	39.73	84.93	0.35	0.51	0.21	1.77	3.32
17	24.13	2.68	33.71	36.81	39.73	84.93	0.35	0.51	0.24	1.76	3.34
18	18.25	2.45	39.51	31.25	39.26	85.15	0.07	0.22	0.17	2.13	3.48
19	18.15	2.44	39.51	31.25	39.26	85.15	0.07	0.25	0.14	2.12	3.50
20	7.27	1.96	41.21	30.02	38.64	85.39	0.10	0.29	0.11	1.60	3.35
21	7.13	2.22	41.05	31.20	37.92	85.07	0.06	0.24	0.17	1.78	3.06
22	7.35	2.20	43.10	29.15	37.92	85.39	0.06	0.26	0.08	1.88	2.86
23	24.81	1.95	35.35	32.07	41.47	86.06	0.01	0.25	0.18	1.58	3.24
24	24.79	1.95	35.70	32.07	41.51	86.06	0.01	0.25	0.18	1.60	3.28
25	24.71	1.91	35.24	32.18	41.47	86.06	0.01	0.25	0.21	1.57	3.26
26	23.49	2.32	34.84	33.23	41.76	85.00	0.04	0.48	0.18	1.55	3.21
27	19.19	1.63	38.04	31.93	39.42	86.06	0.02	0.24	0.23	1.38	3.75
28	18.69	2.11	38.10	31.87	39.42	86.06	0.01	0.26	0.15	1.82	3.56
29	4.49	8.04	35.62	38.64	38.76	62.63	0.47	0.84	2.17	6.81	7.90

Table 6.3. Comparisons of the Pareto optimal solutions with F and Q layout according to the criteria defined by Dvorak *et al.* (1936) for the unrestricted runs. Criteria marked with an * indicate larger the better while all the others indicate the smaller the better (cont.).

Keyboard Layout	Deviation from the balance of hand and finger loads (%)	Percentage of tapping with the same fingers	Percentage of tapping that includes top row	Percentage of tapping that includes bottom row	*Percentage of tapping in the home row	*Percentage of tapping by alternating hands	Percentage of hurdles with the same finger	Percentage of hurdles with adjacent fingers	Percentage of hurdles with remote fingers	Percentage of reach with the same finger	Percentage of reach with adjacent fingers
30	24.69	1.86	35.35	32.07	41.47	86.06	0.01	0.24	0.19	1.52	3.19
31	20.85	1.91	35.74	35.29	38.62	86.06	0.34	0.23	0.19	1.43	3.37
32	20.37	1.97	35.30	31.87	41.36	86.06	0.02	0.24	0.15	1.62	3.29
33	20.27	1.93	35.30	31.87	41.36	86.06	0.02	0.24	0.15	1.61	3.31
34	19.27	2.05	38.15	31.82	39.42	86.06	0.05	0.23	0.18	1.74	3.43
35	19.17	2.01	38.15	31.82	39.42	86.06	0.05	0.23	0.18	1.73	3.45
36	18.59	2.02	38.35	31.87	39.50	86.06	0.01	0.22	0.26	1.74	3.52
37	17.95	1.91	39.16	31.87	38.62	86.06	0.01	0.23	0.16	1.71	3.37
38	17.85	1.87	39.16	31.87	38.62	86.06	0.01	0.23	0.16	1.70	3.39
39	11.05	1.90	34.63	36.40	38.62	85.39	0.38	0.25	0.09	1.33	3.39
40	11.05	1.90	34.63	36.40	38.62	85.39	0.38	0.25	0.09	1.33	3.34
41	10.47	1.91	34.19	32.98	41.36	85.39	0.06	0.26	0.03	1.51	3.28
42	9.37	1.98	37.64	33.12	39.26	85.22	0.07	0.24	0.11	1.64	4.45
43	9.37	2.00	37.04	32.93	39.42	85.39	0.09	0.25	0.05	1.63	3.47
44	8.79	1.99	37.05	33.17	39.50	85.22	0.03	0.23	0.12	1.66	4.50
45	8.05	1.83	38.65	33.17	38.47	85.22	0.03	0.24	0.11	1.62	4.39
46	8.05	1.86	38.05	32.98	38.62	85.39	0.05	0.25	0.04	1.60	3.41
47	8.05	1.86	38.05	32.98	38.62	85.39	0.05	0.25	0.04	1.60	3.36
48	7.05	1.90	39.08	33.17	37.92	85.22	0.03	0.24	0.12	1.64	4.43
49	7.03	1.73	38.05	32.98	38.62	85.39	0.06	0.17	0.11	1.43	3.52
50	8.05	2.12	39.16	31.87	38.62	86.06	0.11	0.24	0.05	1.75	3.22
51	8.05	2.06	39.27	31.87	39.11	85.87	0.11	0.24	0.08	1.70	2.75
52	8.03	1.91	37.75	33.28	38.62	86.06	0.05	0.36	0.05	1.70	3.41
53	9.01	1.88	38.48	32.55	38.62	86.06	0.03	0.22	0.19	1.71	3.56
54	6.41	1.84	38.29	34.39	37.42	85.15	0.04	0.41	0.04	1.67	3.64
55	5.01	2.05	38.05	32.98	38.62	85.39	0.05	0.24	0.05	1.74	3.26
56	5.01	2.05	38.05	32.98	38.62	85.39	0.05	0.24	0.05	1.74	3.21
57	4.29	2.09	39.08	32.15	38.64	85.22	0.03	0.25	0.21	1.81	4.23
58	4.59	2.00	39.27	31.96	38.64	85.39	0.05	0.26	0.22	1.75	3.20
59	4.59	2.08	39.27	31.96	38.64	85.39	0.05	0.26	0.22	1.78	3.22
60	3.69	1.85	36.78	34.22	40.06	85.22	0.21	0.40	0.68	1.44	3.93

Table 6.3. Comparisons of the Pareto optimal solutions with F and Q layout according to the criteria defined by Dvorak *et al.* (1936) for the unrestricted runs. Criteria marked with an * indicate larger the better while all the others indicate the smaller the better (cont).

Keyboard Layout	Deviation from the balance of hand and finger loads (%)	Percentage of tapping with the same fingers	Percentage of tapping that includes top row	Percentage of tapping that includes bottom row	*Percentage of tapping in the home row	*Percentage of tapping by alternating hands	Percentage of hurdles with the same finger	Percentage of hurdles with adjacent fingers	Percentage of hurdles with remote fingers	Percentage of reach with the same finger	Percentage of reach with adjacent fingers
E	3.99	1.89	45.48	25.28	40.36	85.39	0.26	0.26	0.36	1.37	2.96
62	2.95	1.86	35.37	35.38	40.08	85.00	0.17	0.51	0.70	1.41	4.11
63	3.05	1.87	35.37	35.38	40.08	85.00	0.17	0.51	0.70	1.45	4.10
64	3.35	1.89	39.18	31.58	40.36	85.15	0.25	0.45	0.49	1.43	3.18
65	4.23	1.88	39.18	31.58	40.36	85.15	0.24	0.32	0.63	1.43	3.25
66	3.91	2.12	39.18	32.02	39.45	85.00	0.23	0.44	0.77	1.71	3.91
67	4.21	2.19	39.18	31.83	39.75	85.15	0.25	0.45	0.77	1.72	2.96
68	20.87	1.96	35.63	35.40	38.62	86.06	0.34	0.24	0.21	1.48	3.44
69	20.39	2.02	35.83	35.40	38.64	86.06	0.37	0.24	0.26	1.46	3.47
70	20.29	1.98	35.83	35.40	38.64	86.06	0.34	0.24	0.29	1.45	3.49
71	19.29	2.10	38.04	31.93	39.42	86.06	0.08	0.24	0.17	1.79	3.50
72	17.87	1.92	39.05	31.93	38.58	86.06	0.05	0.25	0.20	1.70	3.43
73	8.25	1.90	37.75	33.23	38.58	86.06	0.08	0.24	0.21	1.65	3.05
74	7.95	1.89	38.29	32.69	38.58	86.06	0.08	0.28	0.20	1.62	3.03
75	7.23	1.75	37.75	33.23	38.58	86.06	0.09	0.16	0.28	1.48	3.21
76	21.25	2.64	35.70	32.26	41.24	85.15	0.07	0.33	0.15	2.28	3.01
77	19.11	2.13	35.98	31.98	41.24	85.15	0.06	0.24	0.17	1.77	3.27
78	14.83	1.83	36.37	31.59	41.24	85.22	0.03	0.28	0.07	1.47	3.14
79	15.91	1.79	35.02	33.37	40.71	84.33	0.08	0.25	0.07	1.39	4.39
80	12.77	1.99	34.84	33.12	41.24	85.22	0.03	0.19	0.16	1.64	3.11
81	10.99	1.98	36.62	31.34	41.24	85.22	0.03	0.22	0.16	1.63	2.79
82	10.91	1.99	36.62	31.34	41.24	85.22	0.03	0.19	0.19	1.64	2.82
83	10.89	1.91	36.73	31.23	41.24	85.22	0.04	0.23	0.11	1.55	3.19
84	10.41	2.00	36.03	31.39	41.47	85.22	0.03	0.21	0.16	1.62	2.83
85	10.31	2.03	36.14	31.28	41.47	85.22	0.03	0.18	0.16	1.65	2.83
86	11.05	1.98	34.84	33.12	41.24	85.22	0.03	0.19	0.16	1.63	3.84
87	10.47	2.00	34.25	33.17	41.47	85.22	0.03	0.18	0.16	1.62	3.88
88	10.47	2.01	34.44	32.98	41.47	85.39	0.05	0.20	0.17	1.59	2.92
89	7.97	1.91	40.91	30.72	38.76	86.06	0.07	0.37	0.06	1.70	3.40
90	5.53	2.17	36.65	33.57	39.50	86.06	0.23	0.40	0.14	1.65	3.16
91	4.37	5.98	38.84	24.48	44.40	71.20	0.14	0.37	0.61	5.25	7.55

Table 6.4. Comparisons of the Pareto optimal solutions with F and Q layout according to the criteria defined by Dvorak *et al.* (1936) for the restricted runs. Criteria marked with an * indicate larger the better while all the others indicate the smaller the better.

Keyboard Layout	Deviation from the balance of hand and finger loads (%)	Percentage of tapping with the same fingers	Percentage of tapping that includes top row	Percentage of tapping that includes bottom row	*Percentage of tapping in the home row	*Percentage of tapping by alternating hands	Percentage of hurdles with the same finger	Percentage of hurdles with adjacent fingers	Percentage of hurdles with remote fingers	Percentage of reach with the same finger	Percentage of reach with adjacent fingers
F	38.01	6.18	44.51	20.31	31.12	80.38	1.10	4.28	0.34	4.38	0.07
Q	29.73	9.68	49.34	34.07	18.84	48.62	2.60	5.69	4.53	5.61	2.20
1	28.01	0.76	24.10	33.65	41.99	68.42	0.00	0.57	0.88	6.89	0.67
2	27.71	0.79	24.10	33.65	41.99	68.42	0.01	0.59	0.88	6.88	0.66
3	24.91	1.01	26.07	33.65	40.37	70.19	0.00	0.84	0.97	6.15	0.68
4	24.29	0.85	23.71	33.46	40.03	70.62	0.03	0.64	0.88	6.04	0.70
5	9.03	1.10	25.20	31.91	41.93	74.51	0.09	0.77	0.22	4.74	1.47
6	10.91	0.91	28.59	30.44	40.66	72.45	0.01	0.74	1.27	5.07	0.70
7	10.27	0.81	35.25	25.34	40.17	74.37	0.05	0.68	0.66	4.42	0.82
8	15.53	0.94	27.31	29.86	40.17	71.33	0.05	0.76	0.83	5.42	0.62
9	13.45	0.94	26.76	29.86	40.42	71.33	0.01	0.74	0.82	5.39	0.62
10	4.81	4.54	31.67	31.69	36.96	72.56	0.95	3.29	0.48	6.89	1.55
11	13.45	0.94	26.51	31.24	40.17	71.33	0.05	0.76	0.86	5.45	0.69
12	11.91	0.89	28.59	30.91	40.35	72.45	0.01	0.76	1.28	5.05	0.71
13	10.51	0.78	30.31	29.57	38.67	73.91	0.01	0.62	0.69	5.21	0.85
14	21.79	1.02	25.26	31.92	42.48	68.42	0.01	0.69	0.87	7.33	0.67
15	15.65	1.01	27.31	29.86	40.17	70.83	0.08	0.80	0.87	5.54	0.87
16	13.41	0.78	30.31	29.57	38.67	73.91	0.01	0.62	0.75	5.04	0.79
17	12.63	0.93	29.91	29.55	40.35	71.33	0.01	0.78	1.24	5.05	0.72
18	4.79	3.84	30.36	30.82	37.81	71.47	0.83	2.87	0.25	7.27	1.48
19	11.93	0.83	27.31	29.86	39.70	72.90	0.01	0.66	0.18	4.98	1.37
20	9.69	0.97	26.80	34.92	39.15	74.41	0.05	0.74	0.31	4.98	1.49
21	12.01	0.98	26.28	28.83	42.42	71.28	0.01	0.57	0.46	5.43	1.00
22	18.39	0.79	26.91	29.86	41.72	70.29	0.01	0.55	0.81	6.03	0.72
23	5.37	1.96	29.11	34.10	38.61	67.16	0.22	1.70	1.58	7.36	1.93
24	5.37	1.71	27.78	32.41	41.39	68.00	0.13	1.52	1.15	6.51	1.48
25	6.11	1.50	26.96	31.76	43.20	74.71	0.49	0.88	0.24	3.74	0.58
26	5.29	2.23	29.08	30.74	42.54	66.88	0.27	1.84	1.14	6.83	1.27
27	3.97	6.65	35.41	25.86	38.89	57.74	0.60	5.80	0.44	6.93	1.17
28	4.65	7.83	45.42	19.61	32.44	59.15	0.26	6.82	0.70	13.06	0.72
29	14.43	0.84	25.51	33.72	40.15	72.51	0.02	0.51	0.83	5.28	0.75

Table 6.4. Comparisons of the Pareto optimal solutions with F and Q layout according to the criteria defined by Dvorak *et al.* (1936) for the restricted runs. Criteria marked with an * indicate larger the better while all the others indicate the smaller the better (cont).

Keyboard Layout	Deviation from the balance of hand and finger loads (%)	Percentage of tapping with the same fingers	Percentage of tapping that includes top row	Percentage of tapping that includes bottom row	*Percentage of tapping in the home row	*Percentage of tapping by alternating hands	Percentage of hurdles with the same finger	Percentage of hurdles with adjacent fingers	Percentage of hurdles with remote fingers	Percentage of reach with the same finger	Percentage of reach with adjacent fingers
30	4.87	2.40	23.86	37.79	37.37	77.72	0.08	2.05	0.40	4.92	0.97
31	11.67	0.89	28.36	30.27	39.74	72.51	0.01	0.66	0.13	4.33	1.46
32	4.65	7.24	46.59	18.90	32.44	59.15	0.26	6.23	0.51	12.64	0.70
33	18.39	0.80	25.51	30.97	41.43	70.29	0.01	0.54	0.82	6.01	0.74
34	7.31	2.34	25.22	35.24	38.12	76.12	0.08	1.87	0.67	5.41	0.72
35	14.55	0.84	26.73	30.97	39.66	72.51	0.01	0.55	0.82	5.46	0.75
36	12.37	0.90	27.28	31.98	39.50	72.51	0.01	0.72	0.11	4.94	1.11
37	4.23	6.25	34.83	22.25	40.32	61.15	0.42	5.09	0.56	7.22	0.77
38	4.65	7.55	38.04	22.86	37.80	59.85	0.86	6.08	0.40	7.88	1.42
39	7.31	2.35	25.42	35.52	38.12	76.12	0.08	1.88	0.67	5.39	0.96
40	9.69	0.81	27.06	32.76	38.65	74.63	0.09	0.51	0.35	4.96	1.56
41	4.15	5.95	29.03	32.88	38.19	68.96	0.52	5.09	1.79	5.26	0.94
42	4.45	7.15	31.71	25.52	43.96	49.90	0.99	5.34	0.43	9.72	0.93
43	2.99	2.53	31.15	25.94	43.96	77.10	0.05	1.75	0.62	4.54	0.71
44	10.69	0.88	24.73	32.64	39.91	73.93	0.01	0.58	0.19	4.44	1.41
N	3.37	2.53	29.32	28.57	43.96	77.10	0.05	1.75	0.59	4.37	0.98
46	3.37	2.78	36.31	23.49	40.52	76.60	0.20	2.46	0.15	3.10	0.59
47	2.89	1.89	28.20	28.11	42.87	76.36	0.06	1.78	0.30	4.73	0.71
48	10.95	1.05	25.20	33.05	40.17	73.56	0.03	0.86	0.18	4.29	1.40
49	15.39	1.09	26.52	32.53	39.65	72.46	0.05	0.81	0.88	5.19	0.86
50	10.69	0.89	24.24	32.60	39.69	73.93	0.01	0.65	0.24	4.87	0.94
51	13.59	0.89	25.96	32.52	39.15	73.93	0.00	0.59	0.85	4.77	0.75
52	2.75	2.33	29.32	28.57	43.96	77.10	0.06	1.54	0.58	4.42	0.98
53	13.85	1.06	25.96	32.93	39.65	73.56	0.02	0.81	0.85	4.79	0.75
54	3.93	2.95	36.26	23.86	40.52	76.51	0.17	2.49	0.27	3.11	0.81
55	27.11	0.79	23.89	33.88	41.99	68.90	0.02	0.60	0.99	6.98	0.76
56	24.27	0.71	26.07	32.86	40.25	68.42	0.04	0.49	1.23	7.04	0.74
57	18.35	0.90	27.70	32.62	38.29	70.62	0.00	0.77	1.23	6.53	0.68
58	16.87	0.87	27.04	33.20	38.33	71.10	0.03	0.69	1.27	6.35	0.86
59	22.77	0.95	26.80	32.62	40.25	68.42	0.00	0.81	1.25	7.16	0.67
60	7.57	2.51	33.10	27.62	39.60	75.09	0.16	2.10	0.45	6.30	0.73
61	4.45	7.38	33.32	27.02	40.32	50.83	1.18	5.99	0.98	8.98	0.81

There are eleven criteria of keyboard design that Dvorak used while he criticized Q layout. In Table 6.3 and Table 6.4, the developed layouts, Q and F layouts are compared according to these criteria. However, it is very hard to say which one is better than the other since one solution can be good in one criterion while not so good in another criterion. In order to compare the layouts with each other, the scores in all the criteria are normalized such that the best is 0 and the worst is 100 inside that criterion. To do that, in the lower the better criteria: $(\text{value} - \text{min}) / (\text{max} - \text{min})$ conversion is used, and in the higher the better criteria: $(\text{max} - \text{value}) / (\text{max} - \text{min})$ conversion is used. In all the normalized scores, 0 means the best and 100 means the worst. And all these eleven normalized scores are averaged. The results of these normalized scores and the average score for every keyboard layout is shown in Table 6.5. In this table, U represents unrestricted (32 characters) Pareto front solutions while R represents restricted Pareto front solutions.

Table 6.5. Normalized scores of Dvorak criteria for F, Q and all the Pareto optimal solutions in unrestricted (32 characters) and restricted (29 characters) runs. Inside every criterion, the scores are normalized such that the best is 0 and the worst is 100.

Keyboard Layout	Deviation from the balance of hand and finger loads (%) (normalized)	Percentage of tapping with the same fingers (normalized)	Percentage of tapping that includes top row (normalized)	Percentage of tapping that includes bottom row (normalized)	*Percentage of tapping in the home row (inversely normalized)	*Percentage of tapping by alternating hands (inversely normalized)	Percentage of hurdles with the same finger (normalized)	Percentage of hurdles with adjacent fingers (normalized)	Percentage of hurdles with remote fingers (normalized)	Percentage of reach with the same finger (normalized)	Percentage of reach with adjacent fingers (normalized)	Average Normalized Score
E	3.5	13.2	42.2	32.3	15.8	1.8	10.0	13.9	4.5	4.2	15.2	14.2
U - 85	21.4	14.7	24.1	62.7	11.5	2.2	1.2	18.3	2.7	2.9	6.0	15.3
U - 84	21.7	14.4	23.9	63.3	11.5	2.2	1.2	17.9	3.4	2.9	6.0	15.3
U - 15	7.0	14.9	30.7	59.9	18.7	2.4	5.4	18.6	3.8	0.0	8.8	15.5
U - 41	21.9	13.4	20.3	71.3	11.9	1.8	2.3	16.1	4.5	7.2	0.0	15.5
U - 83	23.1	13.4	25.2	62.5	12.4	2.2	1.5	16.7	3.8	6.4	3.7	15.5
U - 81	23.4	14.2	25.0	63.0	12.4	2.2	1.2	18.0	3.6	2.6	6.0	15.6
U - 82	23.1	14.3	25.0	63.0	12.4	2.2	1.2	18.2	2.9	2.8	7.4	15.7
U - 88	21.9	14.5	20.8	71.3	11.5	1.8	1.9	17.4	3.1	3.8	6.5	15.9
U - 56	6.4	14.9	27.8	71.3	22.6	1.8	1.9	19.7	4.0	6.5	0.9	16.2

Table 6.5. Normalized scores of Dvorak criteria for F, Q and all the Pareto optimal solutions in unrestricted (32 characters) and restricted (29 characters) runs. Inside every criterion, the scores are normalized such that the best is 0 and the worst is 100 (cont.).

Keyboard Layout	Deviation from the balance of hand and finger loads (%) (normalized)	Percentage of tapping with the same fingers (normalized)	Percentage of tapping that includes top row (normalized)	Percentage of tapping that includes bottom row (normalized)	*Percentage of tapping in the home row (inversely normalized)	*Percentage of tapping by alternating hands (inversely normalized)	Percentage of hurdles with the same finger (normalized)	Percentage of hurdles with adjacent fingers (normalized)	Percentage of hurdles with remote fingers (normalized)	Percentage of reach with the same finger (normalized)	Percentage of reach with adjacent fingers (normalized)	Average Normalized Score
U - 55	6.4	14.9	27.8	71.3	22.6	1.8	1.9	19.7	4.0	7.0	0.9	16.2
U - 51	15.0	15.1	30.1	65.7	20.7	0.5	4.2	19.1	4.0	2.2	2.3	16.3
U - 20	12.8	13.9	33.9	56.3	22.5	1.8	3.8	17.5	5.1	7.9	3.7	16.3
U - 78	34.3	12.5	24.5	64.3	12.4	2.2	1.2	15.5	4.9	5.9	1.8	16.3
U - 49	12.1	11.4	27.8	71.3	22.6	1.8	2.3	14.8	2.5	9.5	3.7	16.3
U - 22	13.0	16.6	37.6	51.9	25.4	1.8	2.3	22.0	4.5	3.2	2.3	16.4
R - 47	0.4	13.2	8.7	46.7	6.0	25.9	2.3	20.4	5.4	21.0	31.3	16.5
R - 43	0.7	20.3	14.4	35.7	1.7	23.9	1.9	19.9	12.5	19.2	31.3	16.5
U - 58	5.2	14.4	30.1	66.2	22.5	1.8	1.9	19.9	4.5	6.5	8.8	16.5
U - 89	14.8	13.4	33.3	59.9	22.1	0.0	2.7	19.1	6.9	8.3	1.4	16.5
U - 87	21.9	14.4	20.4	72.3	11.5	2.2	1.2	17.9	2.7	12.9	6.0	16.7
U - 59	5.2	15.3	30.1	66.2	22.5	1.8	1.9	20.4	4.5	6.6	8.8	16.7
U - 47	15.0	12.8	27.8	71.3	22.6	1.8	1.9	17.5	4.3	8.0	0.5	16.7
U - 46	15.0	12.8	27.8	71.3	22.6	1.8	1.9	17.5	4.3	8.4	0.5	16.7
U - 80	28.4	14.3	21.6	72.0	12.4	2.2	1.2	18.2	2.9	5.6	6.0	16.8
U - 50	15.0	15.7	29.9	65.7	22.6	0.0	4.2	19.9	4.0	6.6	0.9	16.8
R - 46	1.8	23.1	24.4	23.3	15.2	25.3	7.7	31.1	2.0	5.5	25.8	16.8
U - 75	12.7	11.6	27.2	72.6	22.8	0.0	3.5	15.6	2.2	6.5	11.5	16.9
U - 86	23.5	14.2	21.6	72.0	12.4	2.2	1.2	18.0	2.9	12.5	6.0	17.0
U - 43	18.8	14.4	25.8	71.1	19.5	1.8	3.5	18.0	4.3	9.0	0.9	17.0
U - 74	14.7	13.2	28.3	69.9	22.8	0.0	3.1	17.9	4.9	4.8	7.8	17.0
U - 64	1.7	13.2	30.0	64.2	15.8	2.4	9.6	14.8	8.7	6.3	21.2	17.1
U - 52	15.0	13.4	27.2	72.8	22.6	0.0	1.9	19.1	6.7	8.4	0.9	17.1
U - 90	7.9	16.3	25.1	74.3	19.2	0.0	8.8	18.3	7.6	6.1	5.1	17.1
U - 3	17.1	14.4	26.2	71.3	19.2	1.8	1.9	18.0	4.0	9.7	5.1	17.2
U - 73	15.6	13.3	27.2	72.6	22.8	0.0	3.1	18.3	4.0	5.0	8.3	17.3
R - 25	9.5	8.8	6.3	65.1	4.7	30.3	18.8	6.2	4.0	11.6	25.3	17.3
U - 21	12.4	16.8	33.6	62.3	25.4	2.6	2.3	20.4	4.0	5.1	6.5	17.4

Table 6.5. Normalized scores of Dvorak criteria for F, Q and all the Pareto optimal solutions in unrestricted (32 characters) and restricted (29 characters) runs. Inside every criterion, the scores are normalized such that the best is 0 and the worst is 100 (cont.).

Keyboard Layout	Deviation from the balance of hand and finger loads (%) (normalized)	Percentage of tapping with the same fingers (normalized)	Percentage of tapping that includes top row (normalized)	Percentage of tapping that includes bottom row (normalized)	*Percentage of tapping in the home row (inversely normalized)	*Percentage of tapping by alternating hands (inversely normalized)	Percentage of hurdles with the same finger (normalized)	Percentage of hurdles with adjacent fingers (normalized)	Percentage of hurdles with remote fingers (normalized)	Percentage of reach with the same finger (normalized)	Percentage of reach with adjacent fingers (normalized)	Average Normalized Score
U - 57	4.4	15.4	29.8	67.1	22.5	2.2	1.2	20.9	4.3	16.2	8.3	17.5
U - 53	17.8	13.0	28.6	69.1	22.6	0.0	1.2	19.3	3.6	9.9	7.4	17.5
U - 65	4.2	13.0	30.0	64.2	15.8	2.4	9.2	14.8	5.8	6.9	27.6	17.7
R - 52	0.0	18.1	10.9	49.0	1.7	23.9	2.3	16.6	11.6	18.0	43.8	17.8
U - 44	17.1	14.3	25.8	72.3	19.2	2.2	1.2	18.5	3.8	18.8	4.1	17.9
R - 7	21.3	1.1	22.4	32.6	16.5	31.2	1.9	3.0	13.4	18.0	36.4	18.0
U - 54	10.4	12.6	28.3	78.5	27.3	2.4	1.5	18.6	7.8	10.6	0.5	18.0
U - 45	15.0	12.5	28.9	72.3	23.2	2.2	1.2	17.9	4.0	17.7	3.7	18.1
U - 33	49.7	13.6	22.5	65.7	11.9	0.0	0.8	17.7	4.0	7.5	5.5	18.1
U - 32	50.0	14.0	22.5	65.7	11.9	0.0	0.8	17.9	4.0	7.3	5.5	18.1
U - 48	12.2	13.3	29.8	72.3	25.4	2.2	1.2	18.2	4.0	18.1	4.1	18.2
U - 42	18.8	14.2	27.0	72.0	20.1	2.2	2.7	18.2	4.0	18.3	3.7	18.3
N	1.8	20.3	10.9	49.0	1.7	23.9	1.9	19.9	11.9	17.6	43.8	18.4
R - 54	3.3	25.0	24.3	25.1	15.2	25.5	6.5	31.6	4.7	5.6	35.9	18.4
U - 79	37.3	12.0	21.9	73.3	14.4	4.6	3.1	14.2	4.3	17.7	1.8	18.6
U - 8	46.5	15.8	24.0	65.7	12.4	2.4	2.3	20.2	4.0	7.1	5.1	18.7
U - 77	46.4	15.8	23.8	66.3	12.4	2.4	2.3	20.2	4.0	7.1	6.5	18.8
U - 7	46.7	18.5	25.2	62.6	12.4	2.4	3.1	23.7	4.0	4.7	4.6	18.9
U - 27	46.6	10.3	27.8	66.0	19.5	0.0	0.8	14.1	4.0	11.7	9.2	19.1
U - 30	62.2	12.8	22.6	66.7	11.5	0.0	0.4	16.3	4.0	6.4	7.4	19.1
U - 14	39.3	19.4	34.3	53.0	20.1	2.4	2.7	25.9	3.4	4.2	6.5	19.2
U - 60	2.7	12.7	25.3	77.6	17.0	2.2	8.1	15.0	7.6	13.4	30.0	19.2
U - 38	42.8	12.9	29.9	65.7	22.6	0.0	0.4	19.1	3.8	8.3	6.0	19.2
U - 37	43.1	13.4	29.9	65.7	22.6	0.0	0.4	19.3	3.8	8.1	6.0	19.3
U - 23	62.6	13.8	22.6	66.7	11.5	0.0	0.4	17.2	4.3	6.8	6.9	19.3
U - 67	4.1	16.5	30.0	65.5	18.2	2.4	9.6	19.4	8.7	4.2	34.1	19.3
U - 40	23.5	13.3	21.2	88.7	22.6	1.8	14.6	13.3	4.3	7.8	2.8	19.4
U - 25	62.3	13.4	22.3	67.3	11.5	0.0	0.4	17.1	4.3	7.0	8.3	19.4

Table 6.5. Normalized scores of Dvorak criteria for F, Q and all the Pareto optimal solutions in unrestricted (32 characters) and restricted (29 characters) runs. Inside every criterion, the scores are normalized such that the best is 0 and the worst is 100 (cont.).

Keyboard Layout	Deviation from the balance of hand and finger loads (%) (normalized)	Percentage of tapping with the same fingers (normalized)	Percentage of tapping that includes top row (normalized)	Percentage of tapping that includes bottom row (normalized)	*Percentage of tapping in the home row (inversely normalized)	*Percentage of tapping by alternating hands (inversely normalized)	Percentage of hurdles with the same finger (normalized)	Percentage of hurdles with adjacent fingers (normalized)	Percentage of hurdles with remote fingers (normalized)	Percentage of reach with the same finger (normalized)	Percentage of reach with adjacent fingers (normalized)	Average Normalized Score
U - 24	62.5	13.8	23.2	66.7	11.3	0.0	0.4	17.5	4.3	7.2	6.9	19.4
U - 39	23.5	13.3	21.2	88.7	22.6	1.8	14.6	13.3	4.3	8.3	2.8	19.5
R - 21	26.3	3.0	5.0	50.3	7.7	39.5	0.4	1.3	8.9	27.6	44.7	19.5
U - 35	46.6	14.5	28.0	65.5	19.5	0.0	1.9	19.6	3.8	8.8	6.9	19.5
U - 28	45.2	15.6	27.9	65.7	19.5	0.0	0.4	21.0	4.5	9.9	5.5	19.6
U - 6	59.2	17.7	24.8	63.6	12.4	2.4	2.7	22.6	4.7	3.7	1.8	19.6
U - 34	46.9	14.9	28.0	65.5	19.5	0.0	1.9	19.7	3.8	8.6	6.9	19.6
U - 10	43.4	15.7	28.8	66.3	18.9	2.4	4.6	19.9	0.0	4.5	11.5	19.6
U - 62	0.6	12.8	22.6	83.5	16.9	2.8	6.5	14.5	10.1	15.1	30.9	19.7
U - 36	44.9	14.6	28.4	65.7	19.2	0.0	0.4	19.7	3.6	9.5	10.6	19.7
U - 72	42.9	13.5	29.7	66.0	22.8	0.0	1.9	19.1	4.3	8.6	7.8	19.7
R - 50	22.5	2.0	1.0	69.4	18.4	32.4	0.4	2.5	4.0	22.3	41.9	19.7
U - 13	39.6	19.5	30.6	62.6	20.1	2.4	2.7	26.1	4.0	4.0	5.5	19.7
U - 63	0.9	12.9	22.6	83.5	16.9	2.8	6.5	15.2	10.1	15.0	30.9	19.7
U - 71	46.9	15.5	27.8	66.0	19.5	0.0	3.1	20.5	4.0	9.3	6.5	19.9
U - 12	41.4	16.7	29.4	65.7	20.1	2.4	1.9	22.4	4.3	9.3	5.5	19.9
U - 11	41.6	16.8	29.4	65.7	20.1	2.4	1.9	22.6	4.3	9.1	5.5	20.0
U - 4	61.3	17.6	24.8	63.6	12.4	2.4	2.7	22.4	4.0	6.1	3.2	20.0
U - 66	3.3	15.7	30.0	66.5	19.4	2.8	8.8	19.3	8.5	13.2	34.1	20.1
R - 13	22.0	0.8	12.8	54.1	22.4	32.5	0.4	2.1	14.1	25.5	37.8	20.4
U - 9	43.7	19.3	30.8	62.0	20.1	2.4	2.7	25.8	3.6	9.3	5.1	20.4
R - 9	30.3	2.6	5.9	55.5	15.6	39.3	0.4	3.9	17.0	27.2	27.2	20.5
U - 26	58.8	17.9	21.6	72.6	10.3	2.8	1.5	16.7	9.4	6.5	6.9	20.5
U - 19	43.7	19.3	30.6	62.6	20.1	2.4	2.7	25.8	4.3	9.3	5.1	20.5
U - 18	44.0	19.4	30.6	62.6	20.1	2.4	2.7	25.9	3.6	9.1	6.5	20.6
U - 76	52.5	21.5	23.2	67.7	12.4	2.4	2.7	28.3	6.0	4.6	5.5	20.6
R - 16	30.2	0.8	12.8	54.1	22.4	32.5	0.4	2.1	15.4	23.9	35.0	20.9
R - 5	17.8	4.3	2.9	65.9	9.7	30.8	3.5	4.4	3.6	21.1	66.4	20.9

Table 6.5. Normalized scores of Dvorak criteria for F, Q and all the Pareto optimal solutions in unrestricted (32 characters) and restricted (29 characters) runs. Inside every criterion, the scores are normalized such that the best is 0 and the worst is 100 (cont.).

Keyboard Layout	Deviation from the balance of hand and finger loads (%) (normalized)	Percentage of tapping with the same fingers (normalized)	Percentage of tapping that includes top row (normalized)	Percentage of tapping that includes bottom row (normalized)	*Percentage of tapping in the home row (inversely normalized)	*Percentage of tapping by alternating hands (inversely normalized)	Percentage of hurdles with the same finger (normalized)	Percentage of hurdles with adjacent fingers (normalized)	Percentage of hurdles with remote fingers (normalized)	Percentage of reach with the same finger (normalized)	Percentage of reach with adjacent fingers (normalized)	Average Normalized Score
R - 6	23.1	2.2	9.5	58.5	14.6	36.4	0.4	3.9	27.1	24.2	30.9	21.0
R - 44	22.5	1.9	2.0	69.6	17.6	32.4	0.4	1.4	2.9	18.2	63.6	21.1
R - 51	30.7	2.0	4.4	69.0	20.5	32.4	0.0	1.6	17.7	21.3	33.2	21.2
R - 19	26.0	1.3	7.0	55.5	18.4	35.1	0.4	2.7	2.7	23.3	61.8	21.3
R - 8	36.2	2.6	7.0	55.5	16.5	39.3	1.9	4.3	17.2	27.5	27.2	21.4
R - 36	27.3	2.1	6.9	66.3	19.2	36.2	0.4	3.6	1.1	23.0	49.8	21.4
R - 31	25.3	2.0	9.0	57.6	18.2	36.2	0.4	2.7	1.6	17.2	65.9	21.5
R - 35	33.5	1.4	5.9	61.1	18.5	36.2	0.4	0.9	17.0	27.9	33.2	21.5
I	69.7	18.5	20.4	73.9	10.4	3.0	1.2	18.6	9.8	7.0	5.1	21.6
R - 12	26.0	2.0	9.5	60.8	15.8	36.4	0.4	4.3	27.3	24.0	31.3	21.6
U - 2	69.4	18.1	20.2	74.4	10.4	3.0	1.2	18.5	9.8	7.2	6.5	21.7
R - 17	28.0	2.5	12.0	54.0	15.8	39.3	0.4	4.6	26.4	24.0	31.8	21.7
R - 11	30.3	2.6	5.4	62.5	16.5	39.3	1.9	4.3	17.9	27.8	30.4	21.7
U - 31	51.3	13.4	23.3	83.0	22.6	0.0	13.1	14.8	3.8	8.1	7.4	21.9
R - 53	31.5	3.9	4.4	71.1	18.6	33.4	0.8	5.1	17.7	21.5	33.2	21.9
R - 48	23.3	3.8	2.9	71.7	16.5	33.4	1.2	5.8	2.7	16.8	63.1	21.9
R - 22	44.4	0.9	6.2	55.5	10.5	42.1	0.4	0.9	16.8	33.3	31.8	22.1
R - 29	33.1	1.4	3.5	75.1	16.6	36.2	0.8	0.3	17.2	26.2	33.2	22.1
U - 68	51.4	13.9	23.1	83.6	22.6	0.0	13.1	15.6	4.0	8.7	8.3	22.2
U - 70	49.7	14.2	23.5	83.6	22.5	0.0	13.1	15.2	4.0	9.2	12.0	22.5
U - 69	50.0	14.6	23.5	83.6	22.5	0.0	14.2	15.3	4.0	9.0	10.6	22.5
R - 33	44.4	1.0	3.5	61.1	11.6	42.1	0.4	0.8	17.0	33.1	32.7	22.5
R - 60	13.7	20.1	18.2	44.2	18.8	29.3	6.2	25.4	8.7	35.9	32.3	23.0
R - 15	36.6	3.3	7.0	55.5	16.5	40.7	3.1	4.9	18.1	28.7	38.7	23.0
U - 5	48.7	18.4	25.9	79.9	23.4	2.4	15.4	20.5	3.8	8.0	7.8	23.1
R - 40	19.7	1.1	6.5	70.2	22.5	30.5	3.5	0.3	6.5	23.1	70.5	23.1
R - 49	35.8	4.2	5.4	69.0	18.6	36.3	1.9	5.1	18.3	25.3	38.2	23.5
R - 20	19.7	2.9	6.0	81.2	20.5	31.1	1.9	3.9	5.6	23.3	67.3	24.0

Table 6.5. Normalized scores of Dvorak criteria for F, Q and all the Pareto optimal solutions in unrestricted (32 characters) and restricted (29 characters) runs. Inside every criterion, the scores are normalized such that the best is 0 and the worst is 100 (cont.).

Keyboard Layout	Deviation from the balance of hand and finger loads (%) (normalized)	Percentage of tapping with the same fingers (normalized)	Percentage of tapping that includes top row (normalized)	Percentage of tapping that includes bottom row (normalized)	*Percentage of tapping in the home row (inversely normalized)	*Percentage of tapping by alternating hands (inversely normalized)	Percentage of hurdles with the same finger (normalized)	Percentage of hurdles with adjacent fingers (normalized)	Percentage of hurdles with remote fingers (normalized)	Percentage of reach with the same finger (normalized)	Percentage of reach with adjacent fingers (normalized)	Average Normalized Score
R - 34	12.9	18.2	2.9	82.8	24.6	26.5	3.1	21.8	13.6	27.4	31.8	24.2
R - 30	6.0	18.8	0.3	95.7	27.5	22.3	3.1	24.6	7.6	22.8	43.3	24.7
U - 16	60.9	22.4	19.6	90.2	18.3	3.0	13.5	20.2	10.1	7.6	8.3	24.9
U - 17	60.6	22.0	19.4	90.7	18.3	3.0	13.5	20.1	10.1	7.8	9.7	25.0
R - 14	54.0	3.5	3.0	66.0	7.5	47.1	0.4	3.2	18.1	45.6	29.5	25.3
R - 39	12.9	18.3	3.3	84.2	24.6	26.5	3.1	22.0	13.6	27.2	42.9	25.3
R - 4	61.1	1.6	0.0	73.8	17.1	41.2	1.2	2.4	18.3	33.4	30.9	25.5
R - 57	44.2	2.1	7.7	69.5	23.9	41.2	0.0	4.4	26.2	38.0	30.0	26.1
R - 58	40.0	1.8	6.5	72.4	23.7	40.0	1.2	3.2	27.1	36.3	38.2	26.4
R - 3	62.8	3.3	4.6	74.7	15.8	42.4	0.0	5.5	20.4	34.4	30.0	26.7
R - 2	70.8	0.9	0.8	74.7	9.4	47.1	0.4	1.6	18.3	41.4	29.0	26.8
R - 1	71.6	0.6	0.8	74.7	9.4	47.1	0.0	1.3	18.3	41.5	29.5	26.8
R - 55	69.1	0.9	0.3	75.9	9.4	45.8	0.8	1.7	20.8	42.3	33.6	27.3
R - 56	61.0	0.0	4.6	70.7	16.2	47.1	1.5	0.0	26.2	42.9	32.7	27.5
R - 59	56.8	2.7	6.0	69.5	16.2	47.1	0.0	5.1	26.6	44.0	29.5	27.6
R - 24	7.4	11.1	7.9	68.4	11.8	48.2	5.0	16.3	24.4	37.9	66.8	27.8
R - 26	7.2	16.9	10.4	60.0	7.3	51.2	10.4	21.3	24.2	40.9	57.1	27.9
U - 91	4.6	58.8	29.3	28.3	0.0	39.7	5.4	75.2	6.9	47.7	26.7	29.3
R - 18	5.8	34.9	12.9	60.4	25.8	39.0	31.9	37.6	4.3	45.1	66.8	33.1
R - 37	4.2	61.8	21.5	17.0	16.0	66.5	16.2	72.7	11.2	44.6	34.1	33.2
R - 23	7.4	13.9	10.5	77.0	22.7	50.5	8.5	19.1	34.0	45.9	87.6	34.3
R - 10	5.8	42.7	15.4	64.8	29.1	36.1	36.5	44.2	9.4	41.5	70.0	36.0
R - 41	4.0	58.4	10.3	70.8	24.3	45.7	20.0	72.7	38.7	26.0	41.9	37.5
R - 27	3.5	66.2	22.7	35.3	21.6	75.6	23.1	83.9	8.5	41.8	52.5	39.5
F	100	61.0	70.5	12.4	52.0	15.2	42.3	59.9	6.3	17.6	1.8	39.9
R - 42	4.8	71.8	15.5	33.5	1.7	96.6	38.1	76.6	8.3	68.3	41.5	41.5
R - 38	5.4	76.3	27.8	20.1	25.8	70.0	33.1	88.3	7.6	50.9	64.1	42.7
R - 32	5.4	72.8	44.3	0.0	46.8	71.9	10.0	90.7	10.1	96.0	30.9	43.5

Table 6.5. Normalized scores of Dvorak criteria for F, Q and all the Pareto optimal solutions in unrestricted (32 characters) and restricted (29 characters) runs. Inside every criterion, the scores are normalized such that the best is 0 and the worst is 100 (cont.).

Keyboard Layout	Deviation from the balance of hand and finger loads (%) (normalized)	Percentage of tapping with the same fingers (normalized)	Percentage of tapping that includes top row (normalized)	Percentage of tapping that includes bottom row (normalized)	*Percentage of tapping in the home row (inversely normalized)	*Percentage of tapping by alternating hands (inversely normalized)	Percentage of hurdles with the same finger (normalized)	Percentage of hurdles with adjacent fingers (normalized)	Percentage of hurdles with remote fingers (normalized)	Percentage of reach with the same finger (normalized)	Percentage of reach with adjacent fingers (normalized)	Average Normalized Score
R - 61	4.8	74.4	18.6	41.1	16.0	94.1	45.4	86.9	20.6	61.3	35.9	45.4
R - 28	5.4	79.4	42.1	3.6	46.8	71.9	10.0	100	14.3	100	31.8	45.9
U - 29	4.9	81.7	23.1	100	22.1	62.6	18.1	99.8	17.4	51.0	98.6	52.7
Q	76.5	100	100	89.5	100	100	100	82.1	100	29.3	100	88.9

According to the average normalized scores, E layout is best with an average normalized score of 14.2 and Q layout is worst with an average normalized score of 88.9. F layout is also one of the worst layouts according to average normalized scores with a score of 39.9.

In Table 6.6, the normalized scores of Dvorak criteria just for the candidate layouts, F and Q layouts are shown. From this table, it can be seen that E is the best layout considering the Dvorak criteria while N and I layouts are also good layouts. However, F layout is not as good as the candidate layouts while Q layout is by far the worst keyboard layout considering the Dvorak criteria.

Table 6.6. Normalized scores of Dvorak criteria for F, Q and the candidate layouts. Inside every criterion, the scores are normalized such that the best is 0 and the worst is 100.

Keyboard Layout	Deviation from the balance of hand and finger loads (%) (normalized)	Percentage of tapping with the same fingers	Percentage of tapping that includes top row (normalized)	Percentage of tapping that includes bottom row (normalized)	*Percentage of tapping in the home row (inversely normalized)	*Percentage of tapping by alternating hands (inversely normalized)	Percentage of hurdles with the same finger (normalized)	Percentage of hurdles with adjacent fingers (normalized)	Percentage of hurdles with remote fingers (normalized)	Percentage of reach with the same finger (normalized)	Percentage of reach with adjacent fingers (normalized)	Average Normalized Score
E	3.5	13.2	42.2	32.3	15.8	1.8	10.0	13.9	4.5	4.2	15.2	14.2
N	1.8	20.3	10.9	49.0	1.7	23.9	1.9	19.9	11.9	17.6	43.8	18.4
I	69.7	18.5	20.4	73.9	10.4	3.0	1.2	18.6	9.8	7.0	5.1	21.6
F	100	61.0	70.5	12.4	52.0	15.2	42.3	59.9	6.3	17.6	1.8	39.9
Q	76.5	100	100	89.5	100	100	100	82.1	100	29.3	100	88.9

6.6.4. Validation Study 1: Tendon Travel Estimation

In this experiment, tendon travel of main finger flexor muscles (FDP and FDS) are estimated for the considered keyboard layouts and compared with each other. The details of this test is given below:

6.6.4.1. Subjects. Sixteen professional touch typists (9 female and 7 male) were participated in the validation studies. The ages of the participants were between 25 and 43. All subjects, participating in this study, were in good physical health, and had no records of upper extremity, neck or shoulder disorders or pain. All the participants were right handed and used computers at least ten times per week for a total of at least 8 h per week. Four of the subjects were accustomed to F layout while the other 12 subjects were accustomed to Q layout.

For baseline and descriptive purposes, prior to the tests, typing speed of subjects on meaningful texts was measured. The text used for measuring the speed of the subjects was 970 characters long and subjects wrote this twice; first for the familiarization and second for the measuring. Besides, hand length, wrist breadth and all finger lengths of the subjects were measured for both hands using a caliper. Besides that in order to estimate the tendon

travel using the regression equations (Armstrong and Chan, 1978), the joint thickness of the subjects at metacarpalphalangeal, proximal interphalangeal and distal interphalangeal joints (see Figure 2.15) were measured. These characteristic data of the subjects are given in Table 6.7.

Table 6.7. Characteristic data of the subjects who participated in the experimental validation studies. Typing speed is the speed in character per minute (cpm) measured in meaningful text and anthropometric data is given in millimeters.

Subjects		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	$\bar{x} \pm s$ (range)
Accustomed Layout		F	F	F	F	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	
Typing Speed (cpm)		415	336	172	260	184	145	222	311	309	291	246	155	248	150	285	267	250 ± 76 (145 - 415)
Age		38	34	33	43	28	27	30	31	25	25	32	28	30	27	40	31	31 ± 5 (25 - 43)
Gender		F	M	F	F	F	F	F	M	M	F	M	M	M	F	M	F	-
Finger Length	L. Little	49	62	54	56	47	50	49	67	56	51	59	59	64	48	57	51	55 ± 6 (47 - 679)
	L. Ring	61	71	67	70	56	62	59	80	69	62	74	67	76	58	69	63	67 ± 7 (56 - 80)
	L. Middle	66	79	73	76	65	66	68	86	73	70	77	75	82	65	73	70	73 ± 6 (65 - 86)
	L. Index	62	70	68	71	59	61	62	81	70	63	73	67	77	59	70	64	67 ± 6 (59 - 81)
	R. Index	61	70	67	70	56	62	59	81	70	61	71	67	77	58	70	63	66 ± 7 (56 - 81)
	R. Middle	67	77	74	77	61	67	64	86	76	68	77	73	82	63	75	69	72 ± 7 (61 - 86)
	R. Ring	63	73	69	72	58	62	61	80	68	62	73	69	76	59	68	64	67 ± 6 (58 - 80)
	R. Little	50	63	55	58	46	53	48	66	57	54	61	60	63	49	57	53	56 ± 6 (46 - 66)
Wrist Breadth	Left	37	38	41	43	38	33	40	45	41	36	40	36	43	35	40	37	39 ± 3 (33 - 45)
	Right	38	36	42	44	37	34	39	45	42	34	39	34	43	35	40	37	39 ± 4 (34 - 45)
Hand Length	Left	158	179	174	182	155	161	163	208	184	168	190	170	198	156	181	167	175 ± 15 (155 - 208)
	Right	162	178	178	186	153	163	161	206	185	166	187	169	196	156	181	168	175 ± 15 (153 - 206)

6.6.4.2. Equipment and Set up. For the validation studies, a workstation that typists used in daily working was used. In this workstation, each subject performed the tasks on a windows-based personal computer placed on an adjustable workstation, while seated in a fully adjustable chair. The height of the tabletop was 75 cm. The monitor was adjusted so

that the top line of the monitor was at the same level with the horizon from the eyes and approximately 60 cm from the eyes. For the subjects who are short, a foot rest is supplied and adjusted according to the needs of the subjects.

To allow maximum personal comfort and standardize the postures of the subjects, the guidelines of ANSI/HFES 100-2007 standards about “Human Factors Engineering of Computer Workstations” were followed. Then all subjects were asked to adjust the height of the seat and the backrest inclination based on personal preference, and then it was checked and made sure that postural angles of the subjects while typing were within the range listed in Table 4.4.

The keyboard used in the experiments was a standard keyboard with conventional geometry (Figure 2.1). This was the same keyboard that was used in digraph experiments. For supporting the forearm, approximately 15 cm space is provided between the end of the wrist support and the table edge. The keyboard configuration angles and dimensions are listed in Table 4.5.

In all these tests, the same commercial typing program (RapidTyping 4.6.6) was used.

This study aimed to find the best layout that causes the lowest amount of tendon travel while writing the same amount of Turkish text. As explained before in Section 2.5, tendon travel of the FDS and FDP muscles are used as a factor for the pathogenesis of carpal tunnel syndrome. So, smaller tendon travel mainly means lower risk. Tendon travel occurs, because the angles in the wrist and finger joints changes while typing (see Figure 6.7).

To find the tendon travel on every layout, a data glove called ‘CyberGlove II’ with 18 sensors (see Figure 6.8) is used. The CyberGlove II transforms hand and finger motion into real-time digital joint-angle data. It has a sensor resolution of 1 degree and a sensor repeatability of 3 degree. It is wireless, so it does not have wires that can impede movement and slow the study.

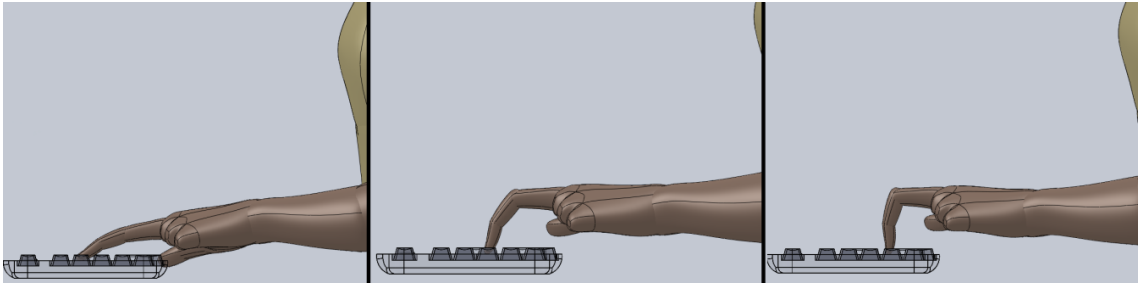


Figure 6.7. Illustration on how the finger joint angles change while typing in top, home and bottom rows.



Figure 6.8. CyberGlove II equipment.

The CyberGlove II device uses 18 sensors (two flexion sensors per finger including thumb, four abduction sensors between the fingers, a palm-arch sensor, a thumb rotation sensor and sensors to measure flexion/extension and abduction/adduction of the wrist) to capture the intricacies of hand and finger movement.

Using the sensors, it was possible to measure the joint angles for the fingers, hand and wrist and transform this data into tendon travel. To do that, the regression equations by Armstrong and Chan (1978) were used. These equations can be found in Table 6.8. During the tests, the joint angle data were collected with 40 Hz frequency for right and left wrist joints and metacarpalphalangeal and proximal interphalangeal joint of all eight fingers. No data was collected for the distal interphalangeal joint since the edges of the glove was open to allow the typists feel and touch the keys. To calculate the tendon travel, DIP joint

angular displacement is estimated as the average of the angular displacements in the MCP and PIP joint angles.

While using the regression equations, it should be noted that there are two regression equations for the tendon travel of wrist joint. If the wrist is in the flexion area, wrist joint (flexion) equation should be used, if the wrist is in the extension area, wrist joint (extension) equation should be used. So from these equations, it seems that the same angular displacement in the wrist joint which is in flexion region requires more tendon travel than the same angular displacement in the wrist joint which is in extension region.

Table 6.8. Regression equations to calculate the tendon travel from the joint motion. Joint angles are in degrees and joint thickness is in millimeters. (Armstrong and Chan, 1978).

	Profundus (FDP)	Superficialis (FDS)
Distal Interphalangeal Joint (DIP)	$0.01902 * \text{Joint Angle} + 0.004211 * \text{Joint Thickness} * \text{Joint Angle}$	$0.03522 * \text{Joint Angle} + 0.004211 * \text{Joint Thickness} * \text{Joint Angle}$
Proximal Interphalangeal Joint (PIP)	$0.09356 * \text{Joint Angle} + 0.004211 * \text{Joint Thickness} * \text{Joint Angle}$	$0.07297 * \text{Joint Angle} + 0.004211 * \text{Joint Thickness} * \text{Joint Angle}$
Metacarpalphalangeal Joint (MCP)	$0.0872 * \text{Joint Angle} + 0.004211 * \text{Joint Thickness} * \text{Joint Angle}$	$0.1034 * \text{Joint Angle} + 0.004211 * \text{Joint Thickness} * \text{Joint Angle}$
Wrist Joint (Flexion)	$0.1323 * \text{Joint Angle} + 0.00404 * \text{Joint Thickness} * \text{Joint Angle}$	$0.1323 * \text{Joint Angle} + 0.005 * \text{Joint Thickness} * \text{Joint Angle}$
Wrist Joint (Extension)	$0.0263 * \text{Joint Angle} + 0.00404 * \text{Joint Thickness} * \text{Joint Angle}$	$0.0263 * \text{Joint Angle} + 0.005 * \text{Joint Thickness} * \text{Joint Angle}$

There were some restrictions regarding the equipment.

First of all, there is only one size for all, both females and males. It was too tight for the males and they had to apply force to abduct and flex their fingers inside the gloves. So after 10 minutes of typing, there was a high fatigue. For females, it was too long and the edges of the glove prevented them to feel the keys and press them. So to overcome this problem, the edges of the gloves were cut (see Figure 6.9).

Another problem was about the calibration. After some time, especially in females the glove slid from the hands and this disrupted the calibration. In order to prevent that, the

bands in the wrist were fastened, but this time this really increased the fatigue. So in the females, it is decided to use latex examination gloves inside the CyberGlove II. This helped us to maintain the calibration longer.



Figure 6.9. The edges of the fingers were cut to allow the subjects to feel and touch the keys and in female subjects latex examination gloves were worn in order to prevent sliding during the typing

The text used consisted of only lower case letters and did not contain any numerical characters or punctuations. The text was created by simulating the digraph frequencies of the Turkish language (see Appendix E2) to have exactly the same digraph distribution as in Turkish language. This text can be found in Appendix H1.

The length of the text was 2275 characters. This text was not as long as the one that was used in the other validation test; because of the fatigue and calibration issues of CyberGlove II that are mentioned above.

6.6.4.3. Experimental Procedure. It is a well known fact that it is very hard to train touch typists to a new layout due to the carry over effects of the previous layout. Considering the

training time of professional touch typists which takes months, this is not a realistic option in the current case. So another method is used. Since all 5 layouts (F, Q, I, E and N layouts) need to be tested in these validation tests, equivalent texts are formed for each layout.

For instance; think that the typist is accustomed to Q layout and the original text is “boğaziçi”. Then the typist first types “boğaziçi” in Q layout for the Q layout. Then he/she types “ötefnbs” in Q layout for the F layout test. Typing “ötefnbs” on Q layout includes pressing exactly the same keyboard keys as typing “boğaziçi” in F layout (see Figure 6.10).

+	!	"	^	\$	%	&	'	(	)	=	?	-	←	
*.	1	2	3	4	5	6	7	8	9	0	/	.	Backspace	
Tab	←	Q	W	E	R	T	Y	U	I	O	P	Ğ	Ü	Enter
Caps Lock	↑	A	S	D	F	G	H	J	K	L	Ş	İ	;	←
Shift	>	Z	X	C	V	B	N	M	Ö	Ç	:	.	Shift	↑
Ctrl	Win	Alt	Space								Alt Gr	Win	Menu	Ctrl

Writing 'ötefnbs' in Turkish Q layout

+	!	"	^	\$	%	&	'	(	)	=	?	-	←	
* .	1	2	3	4	5	6	7	8	9	0	/	.	Backspace	
Tab	↩	F	G	Ğ	I	O	D	R	N	H	P	Q	W	Enter ↵
Caps Lock ⬆	U	İ	E	A	Ü	T	K	M	L	Y	Ş	X		
Shift ⬆	>	J	Ö	V	C	Ç	Z	S	B	:	;	Shift ⬆		
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl	

Writing 'boğaziçi' in F layout

Figure 6.10. Writing ‘ötefnbs’ in Turkish Q layout includes pressing the same keyboard keys as writing ‘boğaziçi’ in F layout.

And for the third, fourth and fifth time, the typist types the equivalent texts in Q layout again for the proposed layouts. In this case, the only potential problem here could be

the meaningfulness effect. When the text is meaningful, subjects can write it faster. One of the authors that investigated this effect (Salthouse, 1984) found that, on average, typing time increases by 60% when typing meaningless texts. Nevertheless, this effect is only active when the typist types with his/her accustomed keyboard layout. In the current case, this effect is eliminated by analyzing the results of typists who were accustomed to Q and F layouts separately.

After being familiar with the typing program, each subject began typing with the original text and wrote it in the keyboard layout he/she is accustomed (either Q or F) since the data from text that is written in the accustomed layout is not used in the statistical analysis because of the meaningfulness effect. The purpose for typing text in their accustomed keyboard layout was just for getting more familiar with the experimental procedure and also for seeing the effect of meaningfulness in typing. So, 4 subjects began typing with F layout and 12 subjects began typing with Q layouts. Therefore in the statistical analysis, we have 12 F layout data and 4 Q layout data which are analyzed separately.

The order of all the other four equivalent texts is randomized for each subject to reduce the experimental error. Between each test, there was at least a 15 minutes break to reduce the fatigue effect on the response (tendon travel).

6.6.4.4. Results and Discussion. Descriptive statistics (mean, standard deviation and range) of tendon travel data that are calculated for each layout and for each finger is shown in Table 6.9 without the data for meaningful texts like the data of F layout that was collected from a typist that is accustomed to F layout. Because of this reason, as can be seen in Table 6.9, there are 12 data for F layout (these are the data of the typists who are accustomed to Q layout) and 4 data for Q layout (these are the data of the typists who were accustomed to F layout). For the others there are 16 data since there were no typists who were accustomed to the developed layouts by the proposed methodology.

Table 6.9. Mean, standard deviation and range data for calculated tendon travel data for each finger and keyboard layout. All the data is in meters. (FDP: flexor digitorum profundus muscle, FDS: flexor digitorum superficialis muscle).

	n	Left Little $\bar{x} \pm s$ (range)	Left Ring $\bar{x} \pm s$ (range)	Left Middle $\bar{x} \pm s$ (range)	Left Index $\bar{x} \pm s$ (range)	Left Hand Fingers: Total of Means	Right Index $\bar{x} \pm s$ (range)	Right Middle $\bar{x} \pm s$ (range)	Right Ring $\bar{x} \pm s$ (range)	Right Little $\bar{x} \pm s$ (range)	Right Hand Fingers: Total of Means	Max. of the means of all fingers	Sum of the means of all fingers	FDP & PDS: Total of Means
F - FDP	12	2.7 ± 0.4 (2.3 - 3.6)	4.8 ± 1.0 (3.2 - 6.8)	5.3 ± 1.0 (3.9 - 6.7)	8.5 ± 1.5 (4.8 - 11.0)	21.3	8.1 ± 1.6 (5.5 - 11.9)	5.0 ± 1.2 (3.2 - 7.3)	3.6 ± 0.8 (2.7 - 5.3)	3.5 ± 0.8 (2.5 - 5.2)	20.2	8.5	41.4	86.7
F - FDS	12	3.1 ± 0.5 (2.6 - 4.1)	5.2 ± 1.2 (3.4 - 7.5)	5.8 ± 1.1 (4.2 - 7.4)	9.1 ± 1.6 (5.1 - 12.1)	23.2	8.7 ± 1.8 (6.2 - 13.0)	5.4 ± 1.3 (3.5 - 8.0)	4.0 ± 0.9 (3.0 - 5.9)	3.9 ± 0.9 (2.8 - 5.9)	22.0	9.1	45.3	
Q - FDP	4	6.0 ± 0.9 (4.7 - 6.9)	3.2 ± 0.7 (2.5 - 4.0)	5.2 ± 1.4 (3.6 - 6.9)	6.3 ± 1.2 (5.0 - 7.5)	20.7	7.4 ± 0.9 (6.3 - 8.3)	5.0 ± 0.8 (4.3 - 6.1)	5.2 ± 0.6 (4.6 - 5.9)	6.1 ± 1.2 (4.9 - 7.4)	23.7	7.4	44.4	93.1
Q - FDS	4	6.6 ± 1.1 (5.1 - 7.6)	3.7 ± 0.8 (2.9 - 4.6)	5.6 ± 1.5 (3.9 - 7.5)	6.9 ± 1.3 (5.4 - 8.3)	22.8	8.1 ± 1.0 (6.7 - 9.1)	5.5 ± 1.0 (4.6 - 6.9)	5.7 ± 0.6 (5.1 - 6.4)	6.6 ± 1.3 (5.4 - 7.9)	25.9	8.1	48.7	
E - FDP	16	4.4 ± 0.7 (3.1 - 6.2)	4.5 ± 1.0 (3.3 - 6.0)	4.6 ± 1.2 (3.1 - 7.5)	5.1 ± 1.1 (3.9 - 7.4)	18.6	5.3 ± 1.2 (3.0 - 7.5)	5.1 ± 1.2 (2.0 - 6.4)	4.8 ± 1.0 (3.4 - 6.7)	4.9 ± 1.1 (3.2 - 6.5)	20.1	5.3	38.7	80.9
E - FDS	16	4.8 ± 0.8 (3.5 - 7.0)	4.9 ± 1.1 (3.6 - 6.7)	5.1 ± 1.3 (3.4 - 8.0)	5.6 ± 1.2 (4.2 - 8.1)	20.4	5.8 ± 1.3 (3.2 - 8.0)	5.5 ± 1.2 (2.3 - 7.0)	5.2 ± 1.1 (3.6 - 7.4)	5.3 ± 1.1 (3.5 - 7.1)	21.8	5.8	42.2	
N - FDP	16	4.1 ± 0.9 (2.2 - 5.5)	4.4 ± 0.9 (3.0 - 6.3)	4.6 ± 1.0 (2.8 - 6.6)	4.8 ± 1.0 (3.4 - 7.5)	17.9	5.1 ± 0.7 (3.7 - 6.5)	4.5 ± 0.8 (3.2 - 5.9)	5.0 ± 0.9 (3.6 - 7.2)	4.7 ± 1.0 (3.0 - 7.2)	19.3	5.1	37.2	77.7
N - FDS	16	4.5 ± 0.9 (2.5 - 6.0)	4.9 ± 1.0 (3.3 - 6.9)	5.0 ± 1.1 (3.1 - 7.1)	5.3 ± 1.1 (3.7 - 8.0)	19.7	5.5 ± 0.7 (4.0 - 6.7)	4.9 ± 0.8 (3.4 - 6.3)	5.5 ± 1.1 (3.9 - 7.9)	5.1 ± 1.1 (3.4 - 7.8)	21.0	5.5	40.5	
I - FDP	16	2.5 ± 0.5 (1.4 - 3.2)	3.9 ± 0.7 (2.8 - 5.2)	4.4 ± 0.7 (3.4 - 5.7)	6.7 ± 1.0 (5.0 - 8.7)	17.5	7.0 ± 1.3 (4.8 - 9.5)	4.6 ± 1.0 (3.1 - 7.3)	4.3 ± 1.0 (3.0 - 6.5)	3.5 ± 1.0 (1.9 - 5.7)	19.4	7.0	36.8	76.9
I - FDS	16	2.8 ± 0.6 (1.6 - 3.7)	4.3 ± 0.8 (3.1 - 5.7)	4.8 ± 0.8 (3.6 - 6.3)	7.2 ± 1.1 (5.4 - 9.5)	19.1	7.6 ± 1.5 (5.3 - 10.4)	4.9 ± 1.0 (3.4 - 7.6)	4.6 ± 1.1 (3.2 - 7.0)	3.8 ± 1.1 (2.1 - 6.2)	20.9	7.6	40.1	

Figure 6.11 and Figure 6.12 that are derived from Table 6.9 show the means of the tendon travel data for all keyboard layouts and fingers for the meaningless texts and Figure 6.13 shows the maximum and sum of the means of all fingers. Here it should be noted that for the same angular displacement, tendon travel of the different fingers would not be the same since tendon travel is a function of both angular displacement and joint thicknesses. So fingers which have thicker joints would have more tendon travel than the other for the same angular displacement.

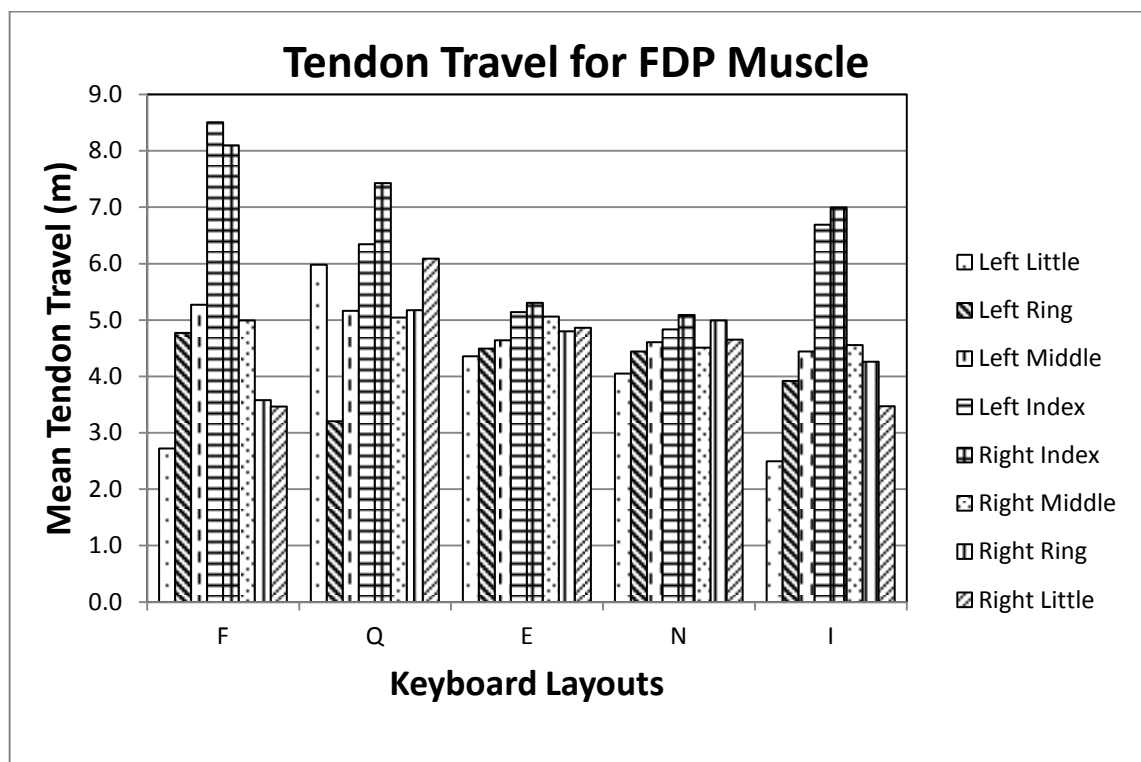


Figure 6.11. Means of the tendon travel data for all keyboard layouts and fingers for the FDP muscle.

As seen in Figure 6.11 and 6.12; for F, Q and I layout the distribution of the tendon travel is non uniform. In F layout, tendon travels of index fingers are extremely higher than the other fingers and layouts. In Q layout, tendon travel data seems random. Tendon travel of left ring finger is very small while left little finger is high. Also in I layout (estimated to be the fastest by our optimization procedure), tendon travel of the index fingers are extremely higher than the other fingers. However, tendon travel of the fingers in E and N layouts are more even across the fingers.

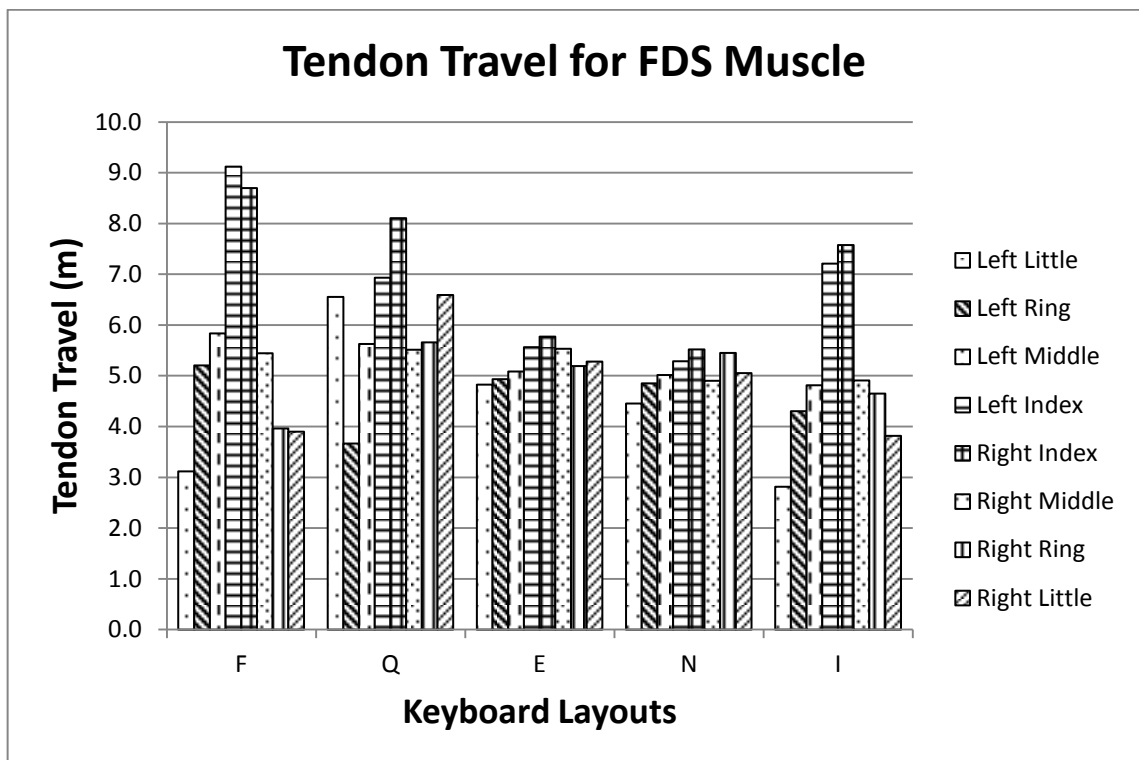


Figure 6.12. Means of the tendon travel data for all keyboard layouts and fingers for the FDS muscle.

In addition, it can be seen in Figure 6.13 that Q layout have the highest total mean tendon travel with 44.4 m for FDP muscle and 48.7 m for FDS muscle. F layout is the second with 41.4 m tendon travel for FDP muscle and 45.3 m for FDS muscle. However, in total there is not so much difference between the candidate layouts E, N and I with approximately 37-39 m of tendon travel for FDP muscle and 40-42 m tendon travel for FDS muscle in total. It seems that in total tendon travel, the best candidate layout (I layout) is 17% shorter (better) than Q layout and approximately %11 shorter (better) than F layout. That is, in I layout the same text was written with the use of shorter tendon travel distance than of all the other layouts.

However; besides total tendon travel of all fingers, tendon travel distribution across the fingers is also important. If the tendon of one finger overworks while others are under loaded, this is also not good. As seen in Figure 6.11, Figure 6.12 and Table 6.9, maximum tendon travel in F layout is highest with 8.5 m for FDP muscle and 9.1 m for FDS muscle for the right index finger's tendon. The reason behind this is that nearly half of the typing is done with index fingers in F layout. Q and I layouts have nearly the same maximum

tendon travel. And E and N layouts resulted in the lowest maximum tendon travel. This means that in these layouts, typing load is distributed more evenly as in the F and I layouts index fingers are overloaded. In these layouts, there is approximately 35-40% decrease in the amount of tendon travel of the hardest working finger compared to F layout.

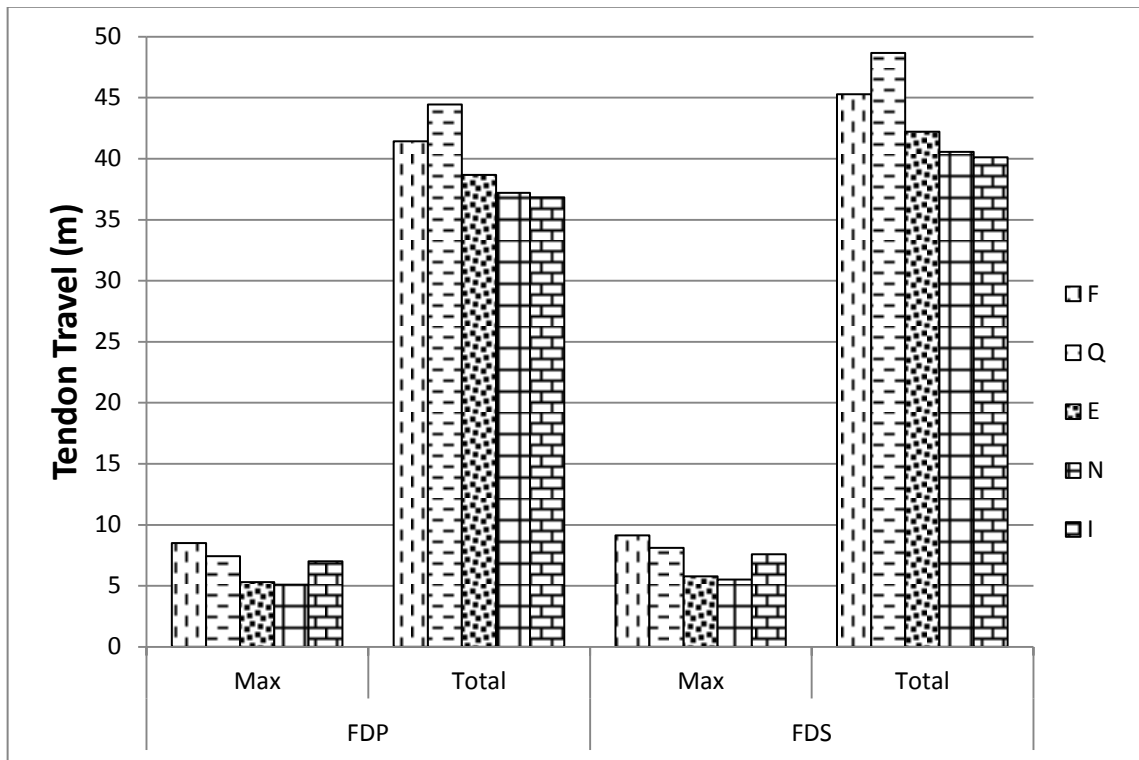


Figure 6.13. Maximum and sum of means of tendon travel data for all fingers and keyboard layouts.

The results above are drawn from descriptive statistics. However, to understand if these differences are significant, a general linear model is formed. In this model, tendon travel is the dependent variable. Subjects are the block factor while finger in each layout and muscle (either FDS or PDP) are the factors.

As explained previously, there are 16 subjects. 4 of these subjects were accustomed to F layout and 12 of these subjects were accustomed to Q layout. Because of the meaningfulness effect that is explained in the previous section, every subject typed faster in their accustomed keyboard layouts. In order to evaluate the layouts fairly, the subjects are divided into two and two statistical analyses are done: one for the typists who are accustomed to F layout and one for the typists who are accustomed to Q layout.

The statistical results table and post-hoc analysis according to Tukey' test for the typist who are accustomed to F layout are shown in Table 6.10 and Table 6.11. According to the results, there is a significant difference in tendon travel between the muscles. FDS muscle has higher tendon travel than the FDP muscle. When the tendon travel of fingers in the layouts is analyzed (see Table 6.11), it is seen that there are significant differences between the layouts.

Table 6.10. ANOVA results table for tendon travel data of F layout typists.

Source of variation	Degrees of freedom	Seq SS	Adj SS	Adj MS	F	p
Finger in layout	39	409.6	409.6	10.5	224.02	0.00
Subjects (Block)	3	55.3	55.3	18.4	891.58	0.00
Muscle	1	15.0	15.0	15.0	100.11	0.00
Error	276	127.2	127.2	0.5		
Total	319	607.1				

S = 0.68 R-Sq = 79.04% R-Sq(adj) = 75.78%

Table 6.11. Grouping information using Tukey method and 95.0% confidence for the considered factors for the data of F layout typists.

Muscle	N	Mean	Grouping
FDS	160	5.12	A
FDP	160	4.69	B

Finger in Layout	N	Mean	Grouping
Right Index in Q layout	8	7.77	A
Left Index in I layout	8	7.06	A B
Left Index in Q layout	8	6.64	A B C
Left Index in F layout	8	6.40	B C D
Right Little in Q layout	8	6.34	B C D
Left Little in Q layout	8	6.27	B C D E
Right Index in F layout	8	6.13	B C D E F
Right Index in I layout	8	6.00	B C D E F G
Right Little in E layout	8	5.50	C D E F G H
Left Index in E layout	8	5.49	C D E F G H
Right Ring in Q layout	8	5.42	C D E F G H I
Right Index in E layout	8	5.41	C D E F G H I
Left Middle in Q layout	8	5.39	C D E F G H I
Right Middle in E layout	8	5.33	C D E F G H I
Right Middle in Q layout	8	5.28	D E F G H I
Right Ring in N layout	8	4.96	E F G H I J

Table 6.11. Grouping information using Tukey method and 95.0% confidence for the considered factors for the data of F layout typists. (cont.).

Finger in Layout (cont.)	N	Mean	Grouping
Right Ring in I layout	8	4.84	F G H I J K
Left Middle in E layout	8	4.76	G H I J K L
Left Middle in N layout	8	4.75	G H I J K L
Right Ring in E layout	8	4.72	G H I J K L M
Left Middle in F layout	8	4.67	H I J K L M
Right Middle in F layout	8	4.66	H I J K L M
Right Little in N layout	8	4.65	H I J K L M
Left Ring in F layout	8	4.65	H I J K L M
Left Little in E layout	8	4.64	H I J K L M
Right Middle in N layout	8	4.59	H I J K L M
Left Index in N layout	8	4.55	H I J K L M
Left Little in N layout	8	4.51	H I J K L M
Left Middle in I layout	8	4.44	H I J K L M
Right Middle in I layout	8	4.31	H I J K L M N
Left Ring in E layout	8	4.28	H I J K L M N
Left Ring in N layout	8	4.13	I J K L M N
Left Ring in I layout	8	3.72	J K L M N O
Right Ring in F layout	8	3.61	K L M N O
Left Ring in Q layout	8	3.44	L M N O
Right Little in I layout	8	3.42	M N O
Right Little in F layout	8	3.07	N O
Left Little in I layout	8	2.58	O
Left Little in F layout	8	2.48	O
Means that do not share a letter are significantly different.			

In Figure 6.14, main effects plot of the fingers in the layouts is shown for the tendon travel data of F layout typists. Since these data are taken from F layout typists, F layout data can be ignored because of the meaningfulness effect. However, when the candidate layouts are compared with Q layout, it can be seen from Figure 6.14 that the tendon travel distribution of the fingers in Q layout is random. Although the difference between the left index and left little finger in Q layout is not significant, the difference between the left little and left ring finger in Q layout is significant (tendon travel for left little finger is higher, see Table 6.11). However, this conflicts with the dexterity and strength capacities of the fingers. The same is true for I layout, the tendon travel distribution is not according to the capacities of the fingers. Besides that, the tendon travel distribution of E and N

layouts are somewhat distributed according to the capacities of fingers. In addition to that, the maximum tendon travel amount of Q layout is significantly larger than both E and N layouts.

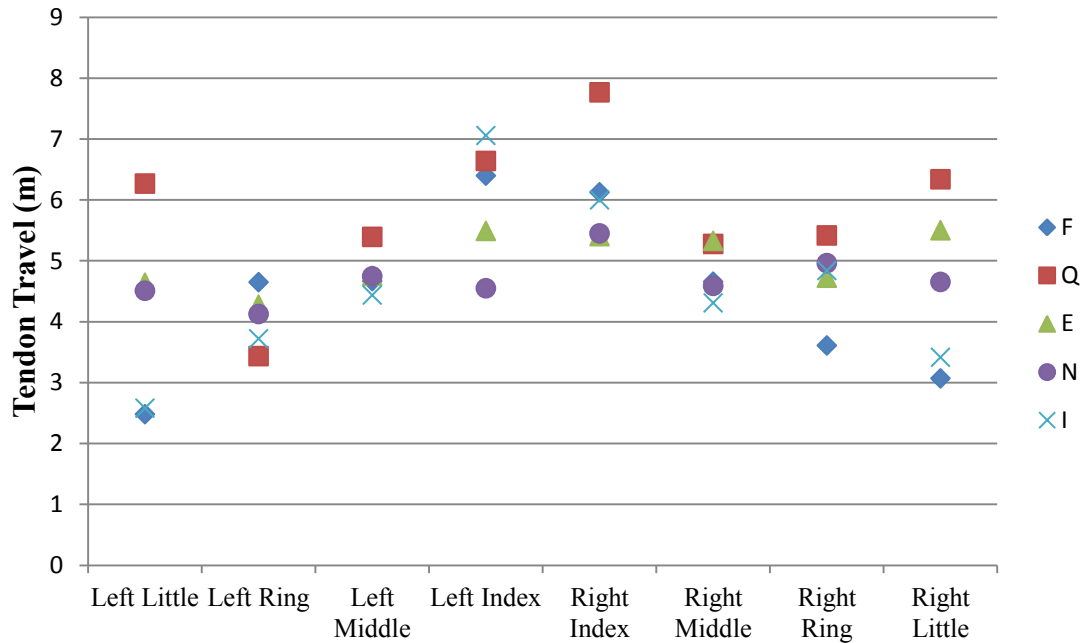


Figure 6.14. Main effects plot of the fingers in the layouts for the tendon travel data of F layout typists

The statistical results table and post-hoc analysis according to Tukey' test for the typist who are accustomed to Q layout are shown in Table 6.12 and Table 6.13. According to the results, there is a significant difference in tendon travel between the muscles. FDS muscle has higher tendon travel than the FDP muscle. When the tendon travel of fingers in the layouts is analyzed (see Table 6.13), it is seen that there are significant differences between the layouts.

Table 6.12. ANOVA results table for tendon travel data of Q layout typists.

Source of variation	Degrees of freedom	Seq SS	Adj SS	Adj MS	F	p
Finger in layout	39	1593.0	1593.0	40.8	63.10	0.00
Subjects (Block)	11	486.0	486.0	44.2	68.25	0.00
Muscle	1	49.2	49.2	49.2	76.06	0.00
Error	908	587.8	587.8	0.6		
Total	959	2716.0				

S = 0.80 R-Sq = 78.36% R-Sq(adj) = 77.14%

Table 6.13. Grouping information using Tukey method and 95.0% confidence for the considered factors for the data of Q layout typists.

Muscle	N	Mean	Grouping
FDS	480	5.34	A
FDP	480	4.89	B
Finger in Layout	N	Mean	Grouping
Left Index in F layout	24	8.81	A
Right Index in F layout	24	8.40	A B
Right Index in I layout	24	7.72	B C
Right Index in Q layout	24	7.11	C
Left Index in I layout	24	6.91	C D
Left Index in Q layout	24	6.11	D E
Left Middle in Q layout	24	5.93	E F
Right Index in E layout	24	5.58	E F G
Left Middle in F layout	24	5.55	E F G
Right Little in Q layout	24	5.43	E F G H
Right Ring in N layout	24	5.31	E F G H
Left Index in E layout	24	5.31	E F G H
Right Middle in E layout	24	5.28	E F G H
Left Little in Q layout	24	5.28	E F G H
Right Index in N layout	24	5.26	E F G H
Left Index in N layout	24	5.23	E F G H
Right Middle in F layout	24	5.22	E F G H I
Right Ring in Q layout	24	5.12	F G H I J
Right Ring in E layout	24	5.09	F G H I J
Left Ring in F layout	24	4.99	G H I J K
Right Little in E layout	24	4.92	G H I J K
Right Little in N layout	24	4.92	G H I J K
Left Middle in E layout	24	4.90	G H I J K
Right Middle in I layout	24	4.87	G H I J K
Left Ring in E layout	24	4.86	G H I J K
Left Middle in N layout	24	4.83	G H I J K
Left Ring in N layout	24	4.82	G H I J K
Right Middle in N layout	24	4.75	G H I J K
Left Middle in I layout	24	4.69	G H I J K
Right Middle in Q layout	24	4.62	H I J K L
Left Little in E layout	24	4.58	H I J K L M
Right Ring in I layout	24	4.33	I J K L M
Left Ring in I layout	24	4.24	J K L M
Left Little in N layout	24	4.17	K L M
Right Ring in F layout	24	3.77	L M N
Right Little in I layout	24	3.72	L M N

Table 6.13. Grouping information using Tukey method and 95.0% confidence for the considered factors for the data of Q layout typists. (cont.).

Finger in Layout (cont.)	N	Mean	Grouping			
Right Little in F layout	24	3.68	M N			
Left Little in F layout	24	2.92	N O			
Left Ring in Q layout	24	2.77	O			
Left Little in I layout	24	2.68	O			
Means that do not share a letter are significantly different.						

In Figure 6.15, main effects plot of the fingers in the layouts is shown for the tendon travel data of Q layout typists. Since these data are taken from Q layout typists, Q layout data can be ignored because of the meaningfulness effect. However, when the other layouts are compared with each other, it is seen that F layout has the highest tendon travel for index fingers. The difference in the tendon travel between the index fingers of F layout and index fingers of E and N layouts are significant. In F layout, the tendon travel difference between right ring and right little fingers is not significant while the difference between left ring and left little fingers is significant. It can easily be seen from Figure 6.15 that the tendon travel distribution among the fingers is not according to the capacities of the fingers in F layout.

For the effect of keyboard layouts on the total tendon travel of all 8 fingers, another general linear model is formed for Q layout typists and F layout typists separately. In these analyses, tendon travel data is taken as the dependent variable while the subjects are blocked; and muscle and keyboard layout are taken as independent variables. So, for every keyboard layout, there are [number of subjects * number of muscles (2) * number of fingers (8)] data. In Table 6.14, post-hoc analysis of these analyses for F layout typists are shown and in Table 6.15, post-hoc analysis of these analyses for Q layout typists are shown.

It is seen from Table 6.14 and 6.15 that total tendon travel is affected from the accustomed keyboard layout. For the F layout typists (see Table 6.14), Q layout has significantly higher total tendon travel than the other layouts. In addition, because of the meaningfulness effect here, although not significant F layout has the minimum tendon

travel. For the Q layout typists (see Table 6.15), F layout has significantly higher total tendon travel than N and I layouts. In addition, because of the meaningfulness effect here, there is no significant difference between Q layout and other layouts. To conclude, Q layout has significantly longer total tendon travel than all of the other layouts, besides I and N layouts have significantly shorter total tendon travel than F layout and Q layout.

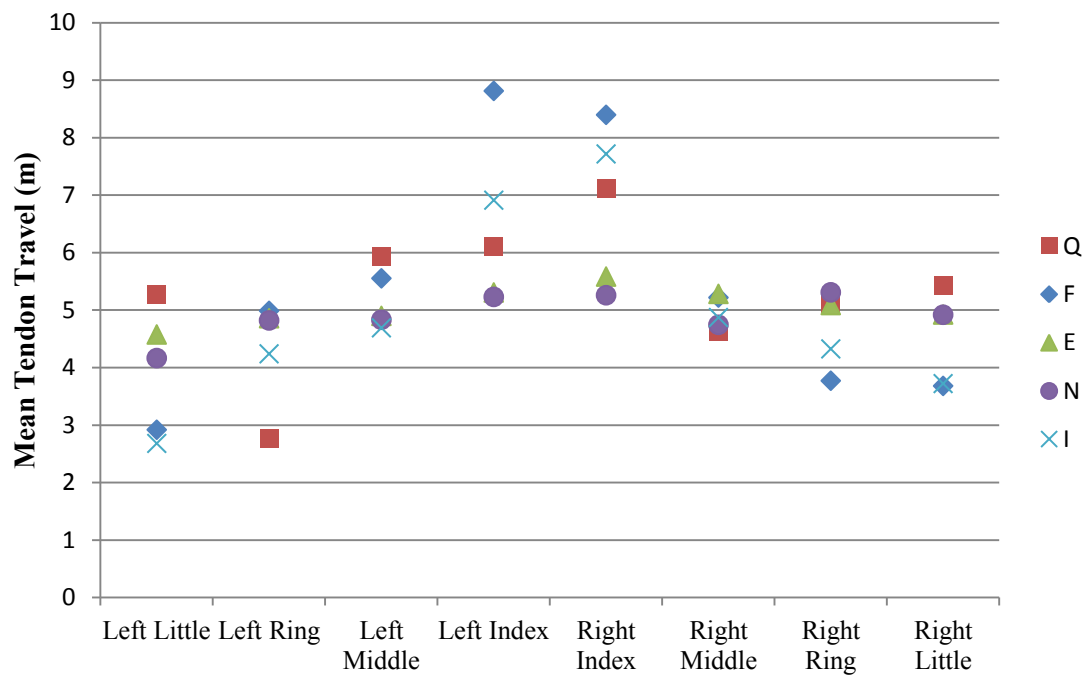


Figure 6.15. Main effects plot of the fingers in the layouts for the tendon travel data of Q layout typists

Table 6.14. Grouping information using Tukey method and 95.0% confidence for the layout factor for the data of F layout typists.

Layout	N	Mean	Grouping
Q	64	5.82	A B B B B
E	64	5.02	
N	64	4.70	
I	64	4.55	
F	64	4.46	
Means that do not share a letter are significantly different.			

Table 6.15. Grouping information using Tukey method and 95.0% confidence for the layout factor for the data of Q layout typists.

Layout	N	Mean	Grouping		
F	192	5.42	A		
Q	192	5.30		A	B
E	192	5.07		A	B
N	192	4.91			B
I	192	4.90			B
Means that do not share a letter are significantly different.					

The examination of the tendon travel data indicates that E and N layouts are the best layouts considering both the total tendon travel of all eight fingers and also the distribution of the tendon travel across the fingers.

6.6.4.5. Summary, Assumptions and Limitations. The validity of the candidate layouts and the methodology is proven with tendon travel estimation tests using CyberGlove II. The best candidate layout is 17% shorter (better) than Q layout and approximately %11 shorter (better) than F layout. The same text was written in the best candidate layout with 17% shorter tendon travel than Q layout and 11% shorter tendon travel than F layout. Besides, the distribution of the tendon travel among the fingers is more even in E and N layouts. In Q layout, the distribution is random while in F layout the most of the load is on the index fingers.

However, there are some limitations regarding that validity test. While calculating the tendon travel of FDP and FDS muscles, angle changes in the distal interphalangeal joint is not measured, however these are estimated as the average of the angle changes in the proximal interphalangeal and metacarpalphalangeal joints. This is due to a restriction of the equipment as CyberGlove II with 18 sensors does not have a distal joint sensor. There is another version with distal joint sensors; however that one has closed finger tips, so the typists cannot feel the keys. So it is decided to use the version with open finger tips although it does not have distal interphalangeal joint sensors. Another limitation of the study is the use of the equipment itself. Typing with equipment when compared with typing with bare hands reduce the performance of typing and increase the fatigue. Because of the fatigue experienced while typing with the equipment, the text is kept short.

6.6.5. Validation Study 2: Typing Speed Estimation

In the previous validation study on tendon travel estimation, healthy typing is the main concern. Although we may expect that healthy typing increases typing performance as well, this needs to be tested. Hence, in this study the aim is to find the best layout in which the typists type the fastest in Turkish texts. The details of this experiment are given below.

6.6.5.1. Subjects. The subject population is the same as the validation study 1 (see Section 6.6).

6.6.5.2. Equipment and Set up. For the validation study, a workstation that typists used in daily working was used. In this workstation, each subject performed the tasks on a windows-based personal computer placed on an adjustable workstation, while seated in a fully adjustable chair. The height of the tabletop was 75 cm. The monitor was adjusted so that the top line of the monitor was at the same level with the horizon from the eyes and approximately 60 cm from the eyes. For the subjects who are short, a foot rest is supplied and adjusted according to the needs of the subjects.

To allow maximum personal comfort and standardize the postures, subjects were informed about ANSI/HFES 100-2007 standard “Human Factors Engineering of Computer Workstations”. Then all subjects were asked to adjust the height of the seat and the backrest inclination based on personal preference, and then it was checked and made sure that postural angles of the subjects while typing were within the range listed in Table 4.4.

The keyboard used in the experiments was a standard keyboard with conventional geometry (Figure 2.1). This was the same keyboard that was used in digraph experiments. For supporting the forearm, approximately 15 cm space is provided between the end of the wrist support and the table edge. The keyboard configuration angles and dimensions are listed in Table 4.5.

In all these tests, the same commercial typing program (RapidTyping 4.6.6) was used.

6.6.5.3. Experimental Procedure. It was a need to do this test apart from the previous validation test because of the previously mentioned limitations of the equipment (CyberGlove II). CyberGlove II was affecting the typists speed and there was a high fatigue after about 10 minutes. So in the previous experiments, our text was short. However, in these experiments subjects typed without gloves and the text was very long with 7812 characters.

The text used again consisted of only lower case letters and did not contain any numerical characters or punctuations. The text was created by simulating the digraph frequencies of the Turkish language (see Appendix E2) to have exactly the same digraph distribution that is calculated using TNC (Aksan et. al, 2012). This text can be found in Appendix H2.

Similar to the validation study 1, equivalent texts were created for each of the keyboard layouts as explained in Section 6.6.4.

Each subject began typing with the original text and wrote it in the keyboard layout he/she is accustomed since the data from text that was written in the accustomed layout was not used in the statistical analysis because of the meaningfulness effect. The order of all the other four equivalent texts was randomized for each subject to reduce the experimental error. Between each test, there was at least a 15 minutes break to reduce the fatigue effect on the typing speed. Each of these tests approximately lasts for 45 minutes on average changing according to the typist's speed.

6.6.5.4. Results and Discussion. The descriptive statistics of the response (typing speed) is shown in Table 6.16. In this table, statistics are given separately for two groups of typists who are accustomed to F and who are accustomed to Q layouts. This is done because of the meaningfulness effect. The collected typing speed data are also summarized by a box plot (Figures 6.16). The box plot depicts mean (circles), median, 1st and 3rd quartile and range values and spread of the data for different layouts for the typists who are accustomed to different layouts.

Table 6.16. Descriptive statistics of the typing speed data (in character per minute) stratified by keyboard layouts and the subjects who are accustomed to different layouts.

	n	F $\bar{x} \pm s$ (range)	I $\bar{x} \pm s$ (range)	E $\bar{x} \pm s$ (range)	N $\bar{x} \pm s$ (range)	Q $\bar{x} \pm s$ (range)
F Layout Typists	4	223 $\pm$ 63 (145 - 291)	209 $\pm$ 37 (169 - 256)	203 $\pm$ 40 (166 - 259)	184 $\pm$ 45 (135 - 240)	162 $\pm$ 35 (125 - 209)
Q Layout Typists	12	144 $\pm$ 30 (106 - 197)	143 $\pm$ 29 (104 - 185)	148 $\pm$ 30 (109 - 192)	141 $\pm$ 27 (103 - 187)	183 $\pm$ 37 (132 - 239)

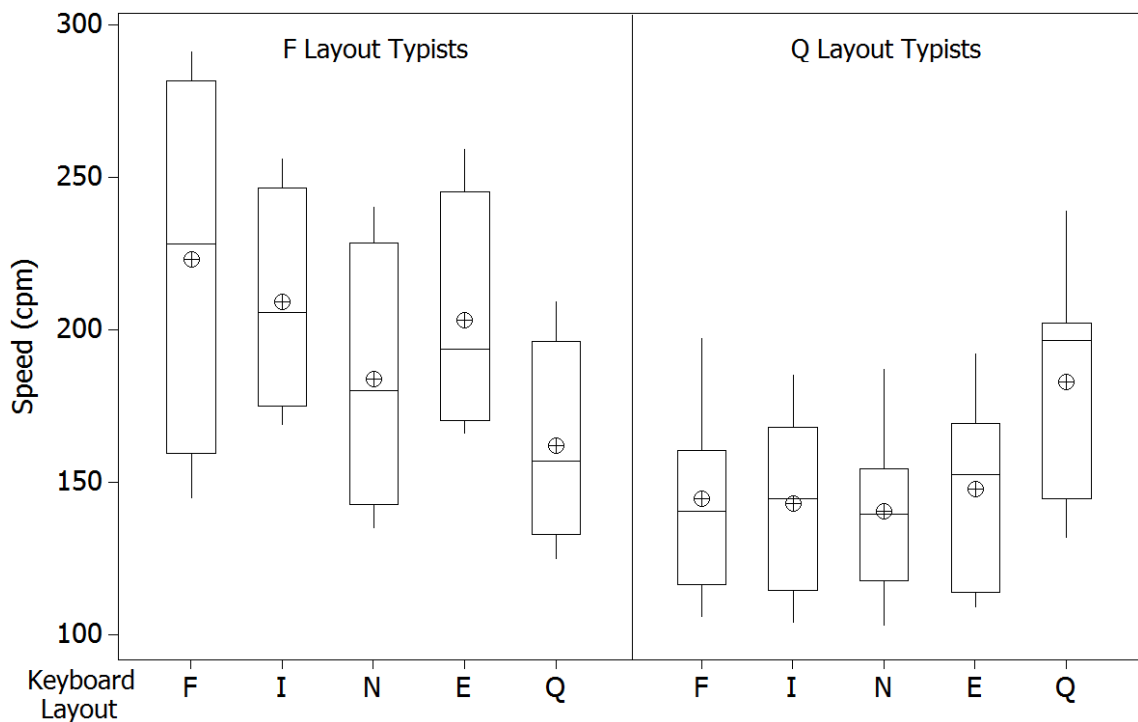


Figure 6.16. Boxplot of typing speed data (in cpm) stratified by keyboard layouts and the subjects who are accustomed to different layouts.

From the descriptive statistics in Table 6.16 and Figure 6.16, it seems like there is a big meaningfulness effect; since the speed of F layout typists is fastest in F layout, and the speed of Q layout typists is fastest in Q layout. When the candidate layouts are compared with F layout for the Q layout typists data (that way there is no meaningfulness effect), it seems E is the fastest and between the others there is little difference. When the candidate layouts are compared with Q layout for the F layout typists data (that way again there is no meaningfulness effect), it seems I and E layouts are the faster than the others and Q layout is by far the slowest layout.

As explained previously, there were 16 subjects. 4 of these subjects were accustomed to F layout and 12 of these subjects were accustomed to Q layout. Because of the meaningfulness effect that is explained in the previous section, every subject typed faster in their accustomed keyboard layouts. In order to evaluate the layouts fairly, the subjects were divided into two and two statistical analyses were done: one for the typists who were accustomed to F layout and one for the typists who were accustomed to Q layout.

The statistical results table and post-hoc analysis according to Tukey' test for the typist who were accustomed to F layout are shown in Table 6.17 and Table 6.18 respectively. As seen F layout is the fastest layout for these typists, because it is the layout they were accustomed to. However when the other layouts are compared, it is seen that all of the candidate layouts are faster than Q layout. The speed is 29% faster for I layout, 25% faster for E layout and 13% faster for the N layout compared to Q layout. Besides that, the differences between I - Q and E - Q layouts are statistically significant even with this sample of 4 typists. This suggests that an optimal keyboard layout can really increase the typing speed.

Table 6.17. ANOVA results table for the speed of typists who were accustomed to F layout.

Source of variation	Degrees of freedom	Seq SS	Adj SS	Adj MS	F	p
Subjects (block)	3	28335	28335	9445	48.93	<0.01
Layout	4	9012	9012	2253	11.67	<0.01
Error	12	2316	2316	193		
Total	19	39663				

S = 13.89 R-Sq = 94.16% R-Sq(adj) = 90.75%

The other statistical results table and post-hoc analysis according to Tukey' test for the typist who were accustomed to Q layout are shown in Table 6.19 and Table 6.20. As seen Q layout is the fastest layout for these typists, because it is the layout they were accustomed to. However when we compare the other layouts, we see that all the other layouts including F layout are indifferent from each other. There is only a difference of 2-5% between these layouts and this is not statistically significant. This suggests that candidate keyboard layouts are at least as fast as F layout and maybe better (on average E layout was 2% faster than F layout).

Table 6.18. Grouping information using Tukey's method and 95,0% confidence for the speed of typing of the typists who were accustomed to F layout. Speed of typing in each layout is given in character per minute (cpm).

Layout	N	Mean	*Grouping
F	4	223.0	A
I	4	209.0	A B
E	4	203.0	A B
N	4	183.8	B C
Q	4	162.0	C
*Means that do not share a common letter are significantly different.			

Table 6.19. ANOVA results table for the speed of typists who were accustomed to Q layout.

Source of variation	Degrees of freedom	Seq SS	Adj SS	Adj MS	F	p
Subjects (block)	11	49757	49757	4523	79.52	<0.01
Layout	4	14863	14863	3716	65.32	<0.01
Error	44	2503	2503	57		
Total	59	67123				

S = 7.54 R-Sq = 96.27% R-Sq(adj) = 95.00%

Table 6.20. Grouping information using Tukey's method and 95,0% confidence for the speed of typing of the typists who were accustomed to Q layout. Speed of typing in each layout is given in character per minute (cpm).

Layout	N	Mean	*Grouping
Q	12	182.8	A
E	12	147.6	B
F	12	144.4	B
I	12	143.0	B
N	12	140.6	B
*Means that do not share a common letter are significantly different.			

6.6.5.5. Summary, Assumptions and Limitations. In this validation test, typing speed is measured as a criterion of performance and efficiency of keyboard layouts. According to the results, typing speed in E and I layouts are significantly faster than Q layout, and there is no significant difference between F and other candidate layouts.

The only limitation of this validation test can be the meaningfulness effect. However, this effect is not active while the analyses are done since the analyses are done separately: one for the F layout typists and one for the Q layout typists.

6.6.6. Summary of Validation Studies

In one of the validation studies, tendon travel of all eight fingers were measured while the subjects were writing in three candidate layouts as well as F and Q layouts. According to the results, in F, Q and I layouts the distribution of the tendon travel is non uniform. However, in E and N layouts, it is nearly distributed according to the capacities of the fingers with little deviations such as in N layout right little finger has a slightly higher tendon travel than the right middle finger (see Figure 6.13 and Figure 6.14).

Total tendon travel is lowest in I layout, however the difference between I and N is not much. E layout has a little higher tendon travel than N layout and it is better than F and Q layouts. Being a random keyboard layout, Q layout has the highest tendon travel amongst all layouts (see Figure 6.12). To conclude, N layout is the best layout when we both consider the total tendon travel and the distribution among fingers. However, E layout is also favored when the tendon travel data is considered.

In the validation studies considering typing speed, Q layout is found to be significantly slower than the others. However, the differences between the other layouts were not statistically significant. However, although not significant, there are some differences. E layout is found to be the fastest. It was 2% faster than F and I layout, 6% faster than N layout and 25% faster than Q layout.

So when we consider the validation studies in which typing speed is estimated, the best layout is E layout. However, F and I layouts are also favored layouts considering the typing speed.

To conclude, when both of the validation tests are considered, it seems that E layout is the best layout.

6.7. Choosing the Best Keyboard Layout for Turkish Language

In this chapter, the decision for the best keyboard layout for Turkish language and how this decision is taken is explained.

6.7.1. Comparisons using the Optimization Results

After the completion of the optimization procedure, two Pareto fronts were formed: one for unrestricted run and one for the restricted run (see Figure 6.2). E, I and N layouts were selected from these Pareto fronts. By examining these Pareto fronts in Figure 6.2, these 3 candidate layouts and also F and Q layouts can be compared (see Table 6.21).

Table 6.21. Digraph and monograph penalties of the candidate, F and Q layouts calculated using the model parameters

Layout	Digraph Penalty Score (msec)	Monograph Penalty Score (%)*
E	144	3
I	141	31
N	146	2
F	149	40
Q	170	31

*Percent values indicates the total variability from the optimal loads

As seen from Table 6.21, digraph score of Q layout (170 msec) is higher than the others stating that typing speed is slower. Also the monograph score is high (31%) stating that the distribution of the load among the fingers is not according to the capacities of the fingers. These scores are normal reminding that Q layout is quite a random keyboard layout for Turkish language.

When F layout is examined, digraph score (149 msec) is quite low, nearly as low as the candidate layouts. This shows that typing speed in F layout is high. However, monograph score (40%) is extremely high, even higher than Q layout which is a random keyboard layout. This shows that the distribution of loads among the fingers in F layout is intentionally disrupted by assigning nearly half of the load to the fast index fingers.

I layout has the best layout in digraph score (141 msec). Since I layout has the best digraph score in the optimization, its monograph score is too high (31%). This layout is in fact not a candidate solution for Turkish language since it has a very uneven load distribution like F layout. However, this layout is added to the candidate list as a benchmark in the validation studies.

E and N layouts are best candidate solutions when the optimization results are considered. Both of them have low digraph (144 msec and 146 msec, respectively) and monograph scores (3% and 2%, respectively).

So from the optimization results it seems that E and N layouts are best and should be selected.

6.7.2. Comparisons using the Dvorak's Criteria

As explained in Section 6.6, all the layouts are evaluated using the Dvorak's criteria (see Table 6.3 and 6.4). Below (see Table 6.22) is the summary of the Dvorak's criteria for three candidate layouts as well as F and Q layouts. Besides, in Table 6.6, normalized scores for these 5 keyboard layouts can be seen.

As seen in Table 6.22, all the criteria for all the candidate layouts are better than Q layout. In addition to that, in 9 out of 11 criteria, candidates are also better than F layout.

However, when three candidate layouts are compared with each other using the Dvorak's criteria, it is seen that in 5 criteria out of 11, E layout is the best; in 4 criteria out of 11, N layout is the best and in 2 criteria out of 11, I layout is the best.

When the layouts are compared for their normalized scores as in Table 6.6, it can be seen that E, N and I layouts has smaller scores (14, 18 and 22 respectively) while F layout has a normalized score of 40 and Q layout has a normalized score of 89.

So the evaluation of the keyboard layouts using Dvorak's criteria showed that E and N layouts are better than the other layouts.

Table 6.22. Comparisons of three candidate layouts with F and Q layouts according to the criteria defined by Dvorak *et al.* (1936). Criteria marked with an * indicate larger the better while all the others indicate the smaller the better.

Keyboard Layout	Deviation from the balance of hand and finger loads	Percentage of tapping with the same fingers	Percentage of tapping that includes top row	Percentage of tapping that includes bottom row	*Percentage of tapping in the home row	*Percentage of tapping by alternating hands	Percentage of hurdles with the same finger	Percentage of hurdles with adjacent fingers	Percentage of hurdles with remote fingers	Percentage of reach with the same finger	Percentage of reach with adjacent fingers
E	3.99	1.89	45.48	25.28	40.36	85.39	0.26	0.26	0.36	1.37	2.96
I	27.33	2.37	34.24	33.48	41.75	84.93	0.03	0.50	0.14	1.67	3.26
N	3.37	2.53	29.32	28.57	43.96	77.10	0.05	1.75	0.59	4.37	0.98
F	38.01	6.18	60.11	21.35	31.12	80.38	1.10	0.34	0.07	4.28	4.38
Q	29.73	9.68	75.32	36.57	18.84	48.62	2.60	4.53	2.20	5.69	5.61

6.7.3. Comparisons using the Validation Study 1: Tendon Travel Estimation

In one of the validation studies, tendon travel of all eight fingers were measured while the subjects were writing in three candidate layouts as well as F and Q layouts (see Section 6.6). According to the results, in F, Q and I layouts the distribution of the tendon travel is non uniform. However, in E and N layouts, it is nearly distributed according to the capacities of the fingers with little deviations such as in N layout right little finger has a slightly higher tendon travel than the right middle finger (see Figure 6.13 and 6.14).

Total tendon travel is lowest in I layout, however the difference between I and N is not much. E layout has a little higher tendon travel than N layout and it is better than F and Q layouts. Being a random keyboard layout, Q layout has the highest tendon travel amongst all layouts (see Figure 6.12).

To conclude, N layout is the best layout when we both consider the total tendon travel and the distribution amongst fingers. However, E layout is also favored when the tendon travel data is considered.

6.7.4. Comparisons using the Validation Study 2: Typing Speed Estimation

In the validation studies considering typing speed, Q layout is found to be significantly slower than the others. However, the differences between the other layouts were not statistically significant. However, although not significant, there were some differences. E layout is found to be the fastest. It was 2% faster than F and I layout, 6% faster than N layout and 25% faster than Q layout.

So when the validation study in which typing speed is estimated is considered, the best layout is E layout. However, F and I layouts are also favored layouts considering the typing speed.

6.7.5. Final Decision

According to optimization results and Dvorak's criteria, E and N layouts are better than others. According to tendon travel validation study, N layout is slightly better than E layout. And according to typing speed validation study, E layout is the best. When all of these results are considered, it seems that it is wiser to select the E layout for the optimal and ergonomic keyboard layout for touch typists of Turkish language.

6.8. Application to Other Languages

The proposed methodology can be directly applied to any language whose number of letters in the alphabet is less than or equal to 32. To do that, only monograph and digraph frequencies of Turkish language (Appendix E3) must be replaced with the monograph and digraph frequencies of the considered language. In the mathematical model in Section 4.2, these are corresponding to MF_i and DF_{ik} parameters.

All the procedures are all the same and can be used directly. Since the validation tests also validate the methodology as well as the candidate layouts in Turkish language, there may not be a necessity to do validation tests again for the considered language. However, here it should be reminded again that the keyboard layouts developed from this methodology is only convenient to touch typists of the considered language.

7. CONCLUSIONS, CONTRIBUTIONS AND RECOMMENDATIONS

The conclusions of the related research, its contributions to the literature and typists, and the recommendations for future research are explained here.

7.1. Conclusions

- (i) In this study, a novel methodology for generating ergonomic and optimal keyboard layouts for various languages that will reduce fatigue, improve typing performance and comfort for touch typists is developed. A multi objective mathematical model with two objectives is defined. One of the objectives is related to the speed of typing while the other is related to the distribution of typing load among the fingers according to their capabilities.
- (ii) The ergonomics criteria that are used in the optimization model are defined objectively by monograph and digraph experiments. The experimentally determined penalty parameters are universal that can be used in keyboard layout optimization of any language.
- (iii) Using the developed methodology, optimal and ergonomic keyboard layouts for touch typing for Turkish language are generated. The developed model is solved by an optimization technique, namely “non-dominated sorting genetic algorithm II (NSGA II)”. Based on the optimization results, three of the obtained 152 keyboard layouts that minimize both monograph and digraph penalties are selected as the candidates of the best keyboard layout for Turkish language. These selected layouts are called as I, E and N layouts.
- (iv) According to the optimization results, developed keyboard layouts are far better than Q and F layouts in monograph penalty and far better than Q layout in digraph penalty.
- (v) When the candidate layouts are compared using the Dvorak *et al.*'s (1936) criteria of keyboard design, the developed layouts are far better than Q layout in all the criteria and are better than F layout in 9 of 11 criteria.
- (vi) The candidate keyboard layouts are compared with F and Q layouts through validation studies considering tendon travel of fingers and typing speed as the

criteria. The results indicate that all three candidate layouts are better than the Q layout in both criteria and better than F layout for tendon travel criterion. For typing speed, there is no significant difference between the F and the candidate layouts. To type the same typical Turkish text, it takes 29% (I layout), 25% (E layout) and 13% (N layout) more time and 21% (I layout), 20% (N layout) and 15% (E layout) longer tendon travel in Q layout compared to the three candidate layouts. For the case of F layout, it takes 13% (I layout), 12% (N layout) and 7% (E layout) longer tendon travel distances in F layout compared to the three candidate layouts. However, since the load distribution of I layout is not according to the capacities of the fingers, E layout is selected as the best layout for touch typing in Turkish language.

7.2. Contributions of the Study

The contributions of this study to the science and applications of typing jobs can be stated as the following:

- (i) Proposed mathematical method is new to the literature since the way how the objective function is defined is novel. The objective function contains two penalties: monograph and digraph penalties. Besides, in the current study a Pareto based optimization technique is used to optimize the multi objectives of a keyboard assignment model for the first time. All the studies that used multi objective optimization in keyboard assignment problem until now used aggregating functions.
- (ii) Current study introduces a systematic methodology for generating ergonomic and optimal keyboard layouts for various languages that will reduce fatigue, improve typing performance and comfort for touch typists.
- (iii) In the previous studies (e.g., Eggers et. al, 2003; Yin and Su, 2010), although some good mathematical models are formed to optimize the keyboard layouts, none used objective parameter values to quantify the ergonomics criteria they used in their models. Instead, they used subjective ratings of ergonomists. The current study quantifies the ergonomic criteria used in the keyboard layout design objectively and scientifically through experiments on finger movements to quantify the monograph and digraph penalty scores used in the model.

- (iv) In almost all of the keyboard optimization models, all the digraphs that are pressed with different hands are treated as the same inside their group. However, in this study these digraphs are separated from each other using the data on same hand digraph experiments. Although there is an assumption for this method which is also stated in the limitations, this is new to the literature
- (v) As an application of the methodology, an optimal and ergonomic keyboard layout for Turkish language is developed. This new layout is called as E layout.
- (vi) In addition to quantification of the model parameters, the experimental results also are used for determining the effects of some factors on tapping and typing speed.

7.3. Limitations of the Study

As every study this study has some limitations that are originated from the assumptions, scope and subject characteristics. Although these limitations are explained through the text, they are also summarized as a list below:

- (i) The parameters used to estimate the digraph penalties are based on the experiments performed using a conventional keyboard. Although this seems like a limitation, we strongly believe that the methodology proposed by this study is applicable to alternative keyboard geometry such as split keyboard.
- (ii) The digraph experiment was performed using the touch typing principles. Hence, the optimization results and proposed layouts may be valid for the touch typists. If typist does not type according to the touch typing principles, then the proposed keyboard layouts may not have the same effect on the typing speed and ergonomics of typing. To design a keyboard layout for a different typing method; for instance, two or eight finger typing, all of the digraph experiment should be repeated according to the principles of the corresponding typing method.
- (iii) The proposed methodology can be used in any language which has less than or equal to 32 letters. If the considered language has more than 32 letters, then mathematical formulations and the optimization procedure should be changed to allow assigning more than one letters to each key.
- (iv) In the digraph experiment, subjects were between 19 and 28 years old. Older people were not tested. So if there is an interaction effect between the tapping speed in the

digraph experiments and the age, the digraph parameters do not include that effect. For instance, in the experiments the digraphs of the little fingers were slower than the others, if older people would have a higher tapping rate for their little finger than their ring fingers, then there would be an interaction effect between the digraphs and the age. However, if all the tapping rates decrease with the same rate when people gets older, then this means there is no interaction effect between the digraphs and the age. Note: In the monograph experiments, subjects were between 18 and 85 years old, however no significant interaction effect is found between the tapping rate and the age group.

- (v) In the digraph experiment, because of the experimental setup and procedure it was impossible to consider hit direction. Hence, it was assumed, for instance, pressing key 7 after key 12 has the same digraph tapping rate as pressing key 12 after key 7. However as explained in the text, hit direction can have an effect on tapping rate. Pressing from little finger towards index finger (outside-in) is better than pressing from index finger towards little finger (inside-out).
- (vi) While calculating the digraph penalty scores for the different hands, it is assumed that in order to press two keys on different hands, typist should move his/her fingers from the standard key position to the position of the key. This assumption is true if the typist's replacement span is one or two character. However, as explained in the text, the replacement span of the professional typists is approximately three characters.
- (vii) For the calculations of the tendon travel of FDP and FDS muscles, angular displacements in the distal interphalangeal joints of the fingers are not measured, however these are estimated as the average of the angular displacements in the proximal interphalangeal and metacarpalphalangeal joints. This was due to a restriction of our equipment as CyberGlove II with 18 sensors does not have a distal joint sensor. There is another version with distal joint sensors, that one has closed finger tips, however the typists cannot feel the keys in that version. So it is decided to use the version with open finger tips although it does not have distal interphalangeal joint sensors.

7.4. Recommendations for Future Research

In the context of the current study, the future studies may consider the following:

- (1) Using the proposed methodology and the monograph and digraph frequencies of the considered language, both ergonomic and optimal keyboard layouts can be developed for any language that has 32 letters or less in its alphabet.
- (2) For the languages which have more than 32 characters, a different mathematical model which allows assignment of more than one character in one key can be developed while using the same finger tapping capacity and digraph costs data.
- (3) For the further validation of the proposed keyboard layouts, longitudinal validation studies can be performed. The new learners of touch typing can be divided into different keyboard layout groups. Then, the learning rate, typing speed, etc. can be measured for the different groups to compare the performance of the keyboard layouts.
- (4) The proposed methodology can be adapted to other typing techniques. For these, additional digraph experiments should be performed on the given conditions.

APPENDIX A: MATLAB CODE OF THE PROGRAM USED IN THE MONOGRAPH EXPERIMENT

The program compiled from the code guides the subjects through the experiment and reports the collected data (Screen print-outs are in Turkish since the subjects are taken from Turkish population).

%% Sets of fingers of left hand and right hand and the standard letters in Q layout

LeftFingers={'SOL ISARET' 'SOL ORTA' 'SOL YUZUK' 'SOL SERCE'};

RightFingers={'SAG ISARET' 'SAG ORTA' 'SAG YUZUK' 'SAG SERCE'};

LeftLetters={'F' 'D' 'S' 'A'};

RightLetters={'J' 'K' 'L' 'Ş'};

%% Creating a random order for the fingers to be tested

s = RandStream.create('mt19937ar','seed',sum(100*clock));

Left=randperm(s,4);

Right=randperm(s,4);

%% Inputting characteristic data of the subject and calculation of age of the subject

Gender=input('Cinsiyetinizi giriniz: [E/K]\n', 's');

Date=input('\nDogum tarihinizi (Gun/Ay/Yil) olarak giriniz: \n', 's');

Now=datestr(now,'dd/mm/yy');

a=datenum(Tarih,'dd/mm/yy');

b=datenum(Simdi,'dd/mm/yy');

Age=(b-a)/365.25;

Occupation=input('\nMesleginizi giriniz \n', 's');

Hand=input('\nBaskin elinizi giriniz: [Sag/Sol]\n', 's');

Smoking=input('\nGunde ortalama kac paket sigara iciyorsunuz? Hic icmiyorsaniz, 0 olarak girin\n');

Exercise=input('\nHaftada ortalama kac kez spor yapıyorsunuz? Hic yapmiyorsaniz 0 olarak girin\n');

FingerLength=input('\nOlculen orta parmak uzunlugunuzu mm olarak giriniz: \n');

```

PalmLength=input("\nOlculen el ayasi uzunlugunuzu mm olarak giriniz: \n");
HandBreadth=input("\nOlculen el genisliginizi mm olarak giriniz: \n");
HandLength=PalmLength+FingerLength;

%% Start of the test with the first random left finger
finger=char(LeftFingers(Left(1)));
letter=char(LeftLetters(Left(1)));
fprintf("\n%s PARMAGINIZLA KLAVYEDEKI \"%s\" TUSUNA 1 DAKIKA BOYUNCA
MAKSIMUM\nHIZDA BASIN\n",finger,letter);
P=zeros(8,12,1);
getkey;
start=tic;
final=toc(start);
i=2;
k=5;

for j=1:12
    while(final<k)
        getkey;
        final=toc(start);
        i=i+1;
    end
    k=k+5;
    P(1,j)=i-2;
end

%% Inputting the subjective rating of perceived fatigue for the first finger
D(1)=input("\nBIR DAKIKA SONUNDA ELINIZ VE PARMAKLARINIZDA OLUSAN
YORGUNLUK\nVEYA RAHATSIZLIGI DEGERLENDIRIN:\n");

%% Start of the test with the first random right finger
fprintf("\n30 SANIYE DINLENIN. 30 SANIYE BITTIGINDE HABER VERILECEK.\n")
pause(30);

```

```

finger=char(RightFingers(Right(1)));
letter=char(RightLetters(Right(1)));
fprintf("\n%s PARMAGINIZLA KLAVYEDEKI "%s" TUSUNA 1 DAKIKA BOYUNCA
MAKSIMUM\nHIZDA BASIN\n',finger,letter);

```

```

getkey;
start=tic;
final=toc(start);
i=2;
k=5;

```

```

for j=1:12
    while(final<k)
        getkey;
        final=toc(start);
        i=i+1;
    end
    k=k+5;
    P(2,j)=i-2;
end

```

%% Inputting the subjective rating of perceived fatigue for the first finger

```

D(2)=input("\nBIR DAKIKA SONUNDA ELINIZ VE PARMAKLARINIZDA OLUSAN
YORGUNLUK\nVEYA RAHATSIZLIGI DEGERLENDIRIN:\n');

```

%% Start of the test with the second random left finger

```

fprintf("\n30 SANIYE DINLENIN. 30 SANIYE BITTIGINDE HABER VERILECEK.\n')
pause(30);

```

```

finger=char(LeftFingers(Left(2)));
letter=char(LeftLetters(Left(2)));
fprintf("\n%s PARMAGINIZLA KLAVYEDEKI "%s" TUSUNA 1 DAKIKA BOYUNCA
MAKSIMUM\nHIZDA BASIN\n',finger,letter);

```

```

getkey;
start=tic;
final=toc(start);
i=2;
k=5;

```

```

for j=1:12
    while(final<k)
        getkey;
        final=toc(start);
        i=i+1;
    end
    k=k+5;
    P(3,j)=i-2;
end

```

%% Inputting the subjective rating of perceived fatigue for the first finger

```

D(3)=input('\nBIR DAKIKA SONUNDA ELINIZ VE PARMAKLARINIZDA OLUSAN
YORGUNLUK\nVEYA RAHATSIZLIGI DEGERLENDIRIN:\n');

```

%% Start of the test with the second random right finger

```

fprintf('\n30 SANIYE DINLENIN. 30 SANIYE BITTIGINDE HABER VERILECEK.\n')
pause(30);

```

```

finger=char(RightFingers(Right(2)));
letter=char(RightLetters(Right(2)));
fprintf('\n%s PARMAGINIZLA KLAVYEDEKI "%s" TUSUNA 1 DAKIKA BOYUNCA
MAKSIMUM\nHIZDA BASIN\n',finger,letter);

```

```

getkey;
start=tic;
final=toc(start);
i=2;

```

```
k=5;
```

```
for j=1:12
```

```
    while(final<k)
```

```
        getkey;
```

```
        final=toc(start);
```

```
        i=i+1;
```

```
    end
```

```
k=k+5;
```

```
P(4,j)=i-2;
```

```
end
```

```
%% Inputting the subjective rating of perceived fatigue for the first finger
```

```
D(4)=input("\nBİR DAKİKA SONUNDA ELİNİZ VE PARMAKLARINIZDA OLUŞAN  
YORGUNLUK\nVEYA RAHATSIZLIĞI DEĞERLENDİRİN:\n');
```

```
%% Start of the test with the third random left finger
```

```
fprintf("\n30 SANİYE DİNLENİN. 30 SANİYE BİTTİĞİNDE HABER VERİLECEK.\n')
```

```
pause(30);
```

```
finger=char(LeftFingers(Left(3)));
```

```
letter=char(LeftLetters(Left(3)));
```

```
fprintf("\n%s PARMAGINIZLA KLAVYEDEKİ \"%s\" TUSUNA 1 DAKİKA BOYUNCA  
MAKSİMUM\nHIZDA BASIN\n',finger,letter);
```

```
getkey;
```

```
start=tic;
```

```
final=toc(start);
```

```
i=2;
```

```
k=5;
```

```
for j=1:12
```

```
    while(final<k)
```

```
        getkey;
```

```

        final=toc(start);
        i=i+1;
    end
    k=k+5;
    P(5,j)=i-2;
end

%% Inputting the subjective rating of perceived fatigue for the first finger
D(5)=input('\nBİR DAKIKA SONUNDA ELİNİZ VE PARMAKLARINIZDA OLUSAN
YORGUNLUK\nVEYA RAHATSIZLIĞI DEĞERLENDİRİN:\n');

%% Start of the test with the third random right finger
fprintf('\n30 SANİYE DİNLENİN. 30 SANİYE BİTTİĞİNDE HABER VERİLECEK.\n')
pause(30);

finger=char(RightFingers(Right(3)));
letter=char(RightLetters(Right(3)));
fprintf('\n%s PARMAGINIZLA KLAVYEDEKİ "%s" TUSUNA 1 DAKIKA BOYUNCA
MAKSİMUM\nHIZDA BASIN\n',finger,letter);

getkey;
start=tic;
final=toc(start);
i=2;
k=5;

for j=1:12
    while(final<k)
        getkey;
        final=toc(start);
        i=i+1;
    end
    k=k+5;

```

```
P(6,j)=i-2;
```

```
end
```

```
%% Inputting the subjective rating of perceived fatigue for the first finger
```

```
D(6)=input("\nBİR DAKIKA SONUNDA ELİNİZ VE PARMAKLARINIZDA OLUSAN  
YORGUNLUK\nVEYA RAHATSIZLIĞI DEĞERLENDİRİN:\n');
```

```
%% Start of the test with the fourth random left finger
```

```
fprintf("\n30 SANİYE DİNLENİN. 30 SANİYE BİTTİĞİNDE HABER VERİLECEK.\n")  
pause(30);
```

```
finger=char(LeftFingers(Left(4)));
```

```
letter=char(LeftLetters(Left(4)));
```

```
fprintf("\n%s PARMAĞINIZLA KLAVYEDEKİ \"%s\" TUSUNA 1 DAKIKA BOYUNCA  
MAKSİMUM\nHIZDA BASIN\n",finger,letter);
```

```
getkey;
```

```
start=tic;
```

```
final=toc(start);
```

```
i=2;
```

```
k=5;
```

```
for j=1:12
```

```
    while(final<k)
```

```
        getkey;
```

```
        final=toc(start);
```

```
        i=i+1;
```

```
    end
```

```
k=k+5;
```

```
P(7,j)=i-2;
```

```
end
```

```
%% Inputting the subjective rating of perceived fatigue for the first finger
```

```
D(7)=input('\nBİR DAKIKA SONUNDA ELİNİZ VE PARMAKLARINIZDA OLUSAN  
YORGUNLUK\nVEYA RAHATSIZLIĞI DEĞERLENDİRİN:\n');
```

```
%% Start of the test with the fourth random right finger
```

```
fprintf('\n30 SANİYE DİNLENİN. 30 SANİYE BİTTİĞİNDE HABER VERİLECEK.\n')  
pause(30);
```

```
finger=char(RightFingers(Right(4)));
```

```
letter=char(RightLetters(Right(4)));
```

```
fprintf('\n%s PARMAĞINIZLA KLAVYEDEKİ "%s" TUSUNA 1 DAKIKA BOYUNCA  
MAKSİMUM\nHIZDA BASIN\n',finger,letter);
```

```
getkey;
```

```
start=tic;
```

```
final=toc(start);
```

```
i=2;
```

```
k=5;
```

```
for j=1:12
```

```
    while(final<k)
```

```
        getkey;
```

```
        final=toc(start);
```

```
        i=i+1;
```

```
    end
```

```
k=k+5;
```

```
P(8,j)=i-2;
```

```
end
```

```
%% Inputting the subjective rating of perceived fatigue for the first finger
```

```
D(8)=input('\nBİR DAKIKA SONUNDA ELİNİZ VE PARMAKLARINIZDA OLUSAN  
YORGUNLUK\nVEYA RAHATSIZLIĞI DEĞERLENDİRİN:\n');
```

```
fprintf('\nDeney sona ermiştir. Katıldığınız için teşekkür ederiz.\n')
```

```
%% Calculations of finger tapping data
```

```
WE=zeros(1,8);
```

```
for l=1:8
```

```
    WE(l)=P(l,12);
```

```
end
```

```
Summed=sum(WE);
```

```
for r=1:8
```

```
    for c=12:-1:2
```

```
        P(r,c)=P(r,c)-P(r,c-1);
```

```
    end
```

```
end
```

```
%% Writing to the excel file
```

```
X={'Occupation' 'Gender' 'Dominant Hand' 'Age' 'Finger' 'Period' 'Hand Length' 'Finger  
Length' 'Hand Breadth' 'Smoking' 'Exercise' 'Number of Taps'};
```

```
Y={'Finger' 'Subjective Fatigue'};
```

```
Hand=cellstr(Hand);
```

```
Occupation=cellstr(Occupation);
```

```
Z=[LeftFingers(Left(1)) RightFingers(Right(1)) LeftFingers (Left (2)) RightFingers (Right  
(2)) LeftFingers (Left (3)) RightFingers (Right (3)) LeftFingers (Left (4)) RightFingers  
(Right (4))];
```

```
A1=repmat(Z(1),12,1);
```

```
A2=repmat(Z(2),12,1);
```

```
A3=repmat(Z(3),12,1);
```

```
A4=repmat(Z(4),12,1);
```

```
A5=repmat(Z(5),12,1);
```

```
A6=repmat(Z(6),12,1);
```

```
A7=repmat(Z(7),12,1);
```

```
A8=repmat(Z(8),12,1);
```

```
Q=[A1;A2;A3;A4;A5;A6;A7;A8];
```

```

Period=(1:12)';
U=[P(1,:); P(2,:); P(3,:); P(4,:); P(5,:); P(6,:); P(7,:); P(8,:)];
xlswrite('Results.xlsx',repmat(Occupation,96,1),'A2:A97');
xlswrite('Results.xlsx',repmat(HandLength,96,1),'G2:G97');
xlswrite('Results.xlsx',repmat(FingerLength,96,1),'H2:H97');
xlswrite('Results.xlsx',repmat(HandBreadth,96,1),'I2:I97');
xlswrite('Results.xlsx',repmat(Smoking,96,1),'J2:J97');
xlswrite('Results.xlsx',repmat(Exercise,96,1),'K2:K97');
xlswrite('Results.xlsx',X,'A1:L1');
xlswrite('Results.xlsx',Y,'N1:O1');
xlswrite('Results.xlsx',repmat(Gender,96,1),'B2:B97');
xlswrite('Results.xlsx',repmat(Hand,96,1),'C2:C97');
xlswrite('Results.xlsx',repmat(Age,96,1),'D2:D97');
xlswrite('Results.xlsx',Q,'E2:E97');
xlswrite('Results.xlsx',repmat(Period,8,1),'F2:F97');
xlswrite('Results.xlsx',Z,'N2:N9');
xlswrite('Results.xlsx',D,'O2:O9');
xlswrite('Results.xlsx',U,'L2:L97');

```

```

%% Writing to the screen

```

```

fprintf('\nParmaklarinizin nisbi hizlari en hizlidan en yavasa olmak uzere\nyuzdesel olarak
asagida belirtilmistir:\n')

```

```

WR=cell(8,2);

```

```

for s=1:8

```

```

    WR(s,:)=[Z(s) (WE(s)/Summed)*800];

```

```

end

```

```

WR=sortcell(WR,2);

```

```

fprintf('%s\t\t\t%4.1f\n',WR{1,1},WR{1,2});

```

```

fprintf('%s\t\t\t%4.1f\n',WR{2,1},WR{2,2});

```

```

fprintf('%s\t\t\t%4.1f\n',WR{3,1},WR{3,2});

```

```
fprintf('%s\t\t\t%4.1f\n',WR{4,1},WR{4,2});  
fprintf('%s\t\t\t%4.1f\n',WR{5,1},WR{5,2});  
fprintf('%s\t\t\t%4.1f\n',WR{6,1},WR{6,2});  
fprintf('%s\t\t\t%4.1f\n',WR{7,1},WR{7,2});  
fprintf('%s\t\t\t%4.1f\n',WR{8,1},WR{8,2});  
input('\nBitirmek icin herhangi bir tusa basiniz.','s');
```

APPENDIX B: DIGRAPH EXPERIMENTS

Table B.1. Coefficients table of ANOVA in Section 5.2.2 for digraph experiments.

Term	Coef	SE Coef	t	p
Constant	166.05	0.25	654.57	0.00
Digraph				
20 - 23	62.23	3.87	16.07	0.00
20 - 25	57.41	3.87	14.83	0.00
20 - 22	56.59	3.87	14.62	0.00
18 - 25	56.45	3.94	14.32	0.00
20 - 26	54.41	4.10	13.28	0.00
18 - 27	54.02	3.87	13.95	0.00
20 - 27	53.38	3.87	13.78	0.00
16 - 25	52.91	3.87	13.66	0.00
18 - 26	52.63	3.87	13.59	0.00
21 - 24	51.88	3.87	13.40	0.00
18 - 24	50.88	3.94	12.90	0.00
19 - 25	50.06	3.87	12.93	0.00
16 - 26	48.87	3.94	12.39	0.00
21 - 27	48.52	3.87	12.53	0.00
19 - 26	47.59	3.87	12.29	0.00
20 - 30	46.40	3.94	11.77	0.00
18 - 23	45.52	3.87	11.76	0.00
20 - 31	45.41	3.87	11.73	0.00
17 - 22	45.23	3.94	11.47	0.00
18 - 22	44.74	3.94	11.35	0.00
16 - 22	44.45	3.94	11.27	0.00
19 - 28	43.91	3.87	11.34	0.00
21 - 23	43.88	3.87	11.33	0.00
19 - 30	43.88	3.87	11.33	0.00
21 - 31	43.52	3.87	11.24	0.00
21 - 26	43.22	3.94	10.96	0.00
8 - 14	42.41	3.87	10.95	0.00
17 - 30	41.59	3.94	10.55	0.00
4 - 10	41.56	3.87	10.73	0.00
17 - 23	40.98	3.87	10.58	0.00
20 - 28	40.81	4.10	9.96	0.00
7 - 14	40.73	3.87	10.52	0.00
6 - 11	40.59	3.87	10.48	0.00

Table B.1. Coefficients table of ANOVA in Section 5.2.2 for digraph experiments (cont.).

Term	Coef	SE Coef	t	p
Digraph (cont.)				
19 - 22	40.15	3.94	10.18	0.00
17 - 27	39.77	3.87	10.27	0.00
17 - 29	39.59	3.87	10.22	0.00
18 - 30	39.22	4.02	9.76	0.00
6 - 15	39.09	3.87	10.10	0.00
16 - 30	38.73	3.87	10.00	0.00
8 - 11	38.63	3.87	9.98	0.00
20 - 24	38.55	3.94	9.78	0.00
7 - 10	38.45	3.87	9.93	0.00
17 - 25	38.34	3.94	9.72	0.00
7 - 13	38.23	3.87	9.87	0.00
19 - 31	38.22	4.02	9.51	0.00
21 - 22	37.60	3.94	9.54	0.00
16 - 28	37.48	4.02	9.33	0.00
5 - 11	37.41	3.87	9.66	0.00
9 - 15	37.34	3.87	9.64	0.00
4 - 13	37.34	3.87	9.64	0.00
8 - 15	37.23	3.87	9.62	0.00
5 - 12	36.81	3.87	9.51	0.00
9 - 12	36.59	4.02	9.11	0.00
17 - 31	36.34	3.87	9.39	0.00
4 - 11	36.00	3.94	9.13	0.00
5 - 13	35.73	3.87	9.23	0.00
19 - 23	35.63	3.87	9.20	0.00
8 - 12	35.23	3.87	9.10	0.00
21 - 32	34.78	4.18	8.32	0.00
18 - 29	34.14	3.94	8.66	0.00
20 - 29	33.99	3.94	8.62	0.00
4 - 14	33.91	3.94	8.60	0.00
5 - 14	33.09	3.87	8.55	0.00
16 - 23	32.99	3.94	8.37	0.00
5 - 15	32.81	3.87	8.47	0.00
17 - 26	32.40	4.02	8.06	0.00
19 - 32	31.31	3.87	8.08	0.00
6 - 14	31.20	3.87	8.06	0.00
17 - 28	30.73	3.87	7.94	0.00
17 - 32	30.59	3.94	7.76	0.00
21 - 25	29.95	3.87	7.73	0.00
7 - 11	29.77	3.87	7.69	0.00
1 - 13	29.77	3.87	7.69	0.00

Table B.1. Coefficients table of ANOVA in Section 5.2.2 for digraph experiments (cont.).

Term	Coef	SE Coef	t	p
Digraph (cont.)				
16 - 31	29.52	3.87	7.62	0.00
2 - 14	28.37	3.94	7.20	0.00
6 - 12	27.70	3.87	7.15	0.00
16 - 32	26.92	3.94	6.83	0.00
8 - 10	26.91	3.87	6.95	0.00
21 - 29	25.32	4.10	6.18	0.00
3 - 11	25.09	3.87	6.48	0.00
2 - 10	24.84	3.87	6.42	0.00
3 - 15	24.56	3.87	6.34	0.00
16 - 29	24.45	3.94	6.20	0.00
3 - 12	24.16	3.87	6.24	0.00
18 - 31	23.91	3.87	6.18	0.00
9 - 14	23.88	3.87	6.17	0.00
5 - 10	23.81	3.87	6.15	0.00
19 - 27	23.06	3.87	5.95	0.00
6 - 13	22.20	3.87	5.73	0.00
1 - 14	21.41	3.87	5.53	0.00
21 - 28	20.33	3.94	5.16	0.00
1 - 10	20.23	3.87	5.23	0.00
3 - 13	19.91	3.87	5.14	0.00
19 - 29	19.77	3.94	5.01	0.00
8 - 13	19.73	3.87	5.10	0.00
3 - 10	19.45	3.94	4.93	0.00
20 - 32	19.34	3.94	4.90	0.00
7 - 12	17.89	3.94	4.54	0.00
2 - 11	17.88	3.94	4.53	0.00
1 - 11	17.45	3.87	4.51	0.00
3 - 14	17.41	3.87	4.50	0.00
2 - 13	16.85	3.94	4.27	0.00
18 - 32	16.56	4.02	4.12	0.00
4 - 12	16.34	3.87	4.22	0.00
2 - 15	16.06	3.87	4.15	0.00
2 - 12	14.70	3.87	3.80	0.00
9 - 11	14.11	3.94	3.58	0.00
7 - 15	12.57	4.02	3.13	0.00
4 - 15	8.47	3.94	2.15	0.03
21 - 30	8.27	4.10	2.02	0.04
24 - 27	8.09	3.87	2.09	0.04
18 - 28	7.49	3.94	1.90	0.06
23 - 26	4.77	3.87	1.23	0.22

Table B.1. Coefficients table of ANOVA in Section 5.2.2 for digraph experiments (cont.).

Term	Coef	SE Coef	t	p
Digraph (cont.)				
22 - 32	2.73	3.87	0.71	0.48
4 - 7	1.59	3.87	0.41	0.68
5 - 8	0.59	3.87	0.15	0.88
23 - 27	0.45	3.87	0.12	0.91
23 - 29	0.34	3.87	0.09	0.93
5 - 9	-0.27	3.87	-0.07	0.95
6 - 9	-0.45	3.87	-0.11	0.91
24 - 26	-0.80	3.87	-0.21	0.84
16 - 27	-1.04	3.94	-0.26	0.79
6 - 10	-1.28	4.10	-0.31	0.76
1 - 12	-1.71	3.94	-0.43	0.67
18 - 20	-3.57	4.18	-0.85	0.39
23 - 25	-3.63	3.94	-0.92	0.36
17 - 24	-3.64	4.27	-0.85	0.39
19 - 20	-3.84	3.87	-0.99	0.32
24 - 31	-4.02	3.87	-1.04	0.30
22 - 25	-4.55	3.87	-1.18	0.24
17 - 19	-6.05	3.87	-1.56	0.12
22 - 26	-6.37	3.87	-1.65	0.10
20 - 21	-7.41	3.87	-1.91	0.06
23 - 30	-9.14	3.94	-2.32	0.02
5 - 7	-9.16	3.87	-2.37	0.02
3 - 9	-9.27	3.87	-2.39	0.02
2 - 7	-10.67	3.94	-2.71	0.01
1 - 15	-10.68	4.10	-2.61	0.01
16 - 19	-10.70	3.87	-2.76	0.01
4 - 8	-10.73	3.87	-2.77	0.01
22 - 31	-11.57	4.18	-2.77	0.01
18 - 21	-12.12	3.87	-3.13	0.00
17 - 18	-13.87	3.87	-3.58	0.00
23 - 31	-14.37	3.94	-3.64	0.00
17 - 20	-14.87	3.87	-3.84	0.00
3 - 8	-14.87	3.87	-3.84	0.00
16 - 17	-15.80	3.87	-4.08	0.00
23 - 24	-16.52	3.87	-4.27	0.00
1 - 7	-16.80	3.87	-4.34	0.00
19 - 24	-16.95	4.58	-3.70	0.00
24 - 32	-17.40	4.27	-4.07	0.00
22 - 29	-18.18	3.94	-4.61	0.00
23 - 28	-18.32	4.18	-4.38	0.00

Table B.1. Coefficients table of ANOVA in Section 5.2.2 for digraph experiments (cont.).

Term	Coef	SE Coef	t	p
Digraph (cont.)				
18 - 19	-18.70	3.87	-4.83	0.00
22 - 23	-18.95	3.87	-4.89	0.00
22 - 27	-19.41	3.87	-5.01	0.00
2 - 9	-19.75	3.94	-5.01	0.00
2 - 8	-19.84	3.87	-5.12	0.00
26 - 27	-20.05	3.94	-5.08	0.00
22 - 28	-20.56	3.94	-5.22	0.00
25 - 26	-21.09	3.87	-5.45	0.00
16 - 20	-23.01	3.94	-5.84	0.00
19 - 21	-23.12	3.94	-5.86	0.00
23 - 32	-23.12	3.87	-5.97	0.00
6 - 7	-23.95	3.87	-6.18	0.00
6 - 8	-24.22	3.94	-6.14	0.00
16 - 18	-25.49	3.94	-6.46	0.00
17 - 21	-26.27	3.87	-6.78	0.00
16 - 24	-27.70	4.18	-6.62	0.00
24 - 29	-27.93	4.27	-6.54	0.00
13 - 14	-28.45	3.87	-7.35	0.00
11 - 12	-28.62	3.87	-7.39	0.00
1 - 4	-30.52	4.02	-7.60	0.00
25 - 30	-30.52	4.02	-7.60	0.00
22 - 30	-30.80	4.37	-7.05	0.00
24 - 25	-30.91	3.87	-7.98	0.00
16 - 21	-31.08	3.94	-7.88	0.00
31 - 32	-31.16	3.87	-8.05	0.00
10 - 11	-31.20	3.87	-8.06	0.00
22 - 24	-31.23	3.94	-7.92	0.00
14 - 15	-31.91	3.87	-8.24	0.00
12 - 14	-32.12	3.87	-8.30	0.00
4 - 9	-32.47	4.02	-8.08	0.00
26 - 31	-32.80	4.02	-8.16	0.00
30 - 31	-33.27	3.94	-8.44	0.00
27 - 31	-33.30	3.87	-8.60	0.00
29 - 30	-33.37	3.87	-8.62	0.00
11 - 14	-33.66	3.87	-8.69	0.00
25 - 29	-33.80	3.87	-8.73	0.00
1 - 8	-34.16	3.87	-8.82	0.00
7 - 8	-34.22	3.94	-8.68	0.00
28 - 29	-35.32	4.10	-8.62	0.00
9 - 10	-35.68	4.18	-8.53	0.00

Table B.1. Coefficients table of ANOVA in Section 5.2.2 for digraph experiments (cont.).

Term	Coef	SE Coef	t	p
Digraph (cont.)				
12 - 15	-35.91	3.87	-9.27	0.00
11 - 13	-36.37	3.87	-9.39	0.00
26 - 30	-36.41	4.02	-9.06	0.00
28 - 30	-36.55	3.87	-9.44	0.00
3 - 6	-36.71			
3 - 7	-37.15	3.94	-9.42	0.00
25 - 27	-38.16	3.94	-9.68	0.00
8 - 9	-38.45	3.87	-9.93	0.00
2 - 4	-38.55	3.87	-9.96	0.00
10 - 14	-38.81	3.94	-9.84	0.00
2 - 5	-39.05	3.87	-10.09	0.00
26 - 29	-39.09	3.87	-10.09	0.00
29 - 31	-39.84	3.87	-10.29	0.00
3 - 5	-41.41	3.87	-10.69	0.00
30 - 32	-41.48	3.87	-10.71	0.00
4 - 5	-41.59	3.87	-10.74	0.00
9 - 13	-43.25	4.37	-9.90	0.00
26 - 28	-44.41	4.02	-11.05	0.00
10 - 13	-44.70	3.87	-11.54	0.00
25 - 28	-45.40	3.94	-11.51	0.00
25 - 32	-45.85	3.94	-11.63	0.00
11 - 15	-45.98	3.87	-11.87	0.00
13 - 15	-46.48	3.87	-12.00	0.00
5 - 6	-47.09	3.87	-12.16	0.00
10 - 12	-47.57	4.02	-11.84	0.00
1 - 5	-47.80	3.87	-12.35	0.00
29 - 32	-48.89	4.02	-12.17	0.00
12 - 13	-49.66	3.87	-12.82	0.00
7 - 9	-50.34	3.87	-13.00	0.00
1 - 9	-50.39	4.02	-12.54	0.00
24 - 30	-50.96	3.94	-12.92	0.00
27 - 30	-50.98	3.87	-13.17	0.00
1 - 2	-51.37	3.87	-13.27	0.00
2 - 6	-51.80	3.87	-13.38	0.00
24 - 28	-52.62	3.87	-13.59	0.00
2 - 3	-53.70	3.87	-13.87	0.00
28 - 31	-53.71	3.94	-13.62	0.00
26 - 32	-54.52	3.87	-14.08	0.00
10 - 15	-55.84	3.87	-14.42	0.00
25 - 31	-55.96	4.10	-13.66	0.00

Table B.1. Coefficients table of ANOVA in Section 5.2.2 for digraph experiments (cont.).

Term	Coef	SE Coef	t	p
Digraph (cont.)				
27 - 32	-57.02	3.87	-14.72	0.00
3 - 4	-60.41	3.87	-15.60	0.00
28 - 32	-61.12	3.87	-15.79	0.00
27 - 29	-61.92	4.02	-15.41	0.00
4 - 6	-63.02	3.87	-16.27	0.00
1 - 6	-72.45	3.87	-18.71	0.00
1 - 3	-80.48	3.94	-20.41	0.00
27 - 28	-81.75	4.02	-20.35	0.00
Subject				
Subj. 4	28.41	0.63	44.90	0.00
Subj. 2	18.14			
Subj. 5	4.49	0.62	7.27	0.00
Subj. 6	1.30	0.62	2.12	0.03
Subj. 1	-0.47	0.62	-0.76	0.45
Subj. 8	-20.75	0.62	-33.57	0.00
Subj. 7	-31.12	0.62	-50.52	0.00
Period				
Period	6.04	0.44	13.66	0.00
Period 2	-1.05	0.44	-2.39	0.02
Period 3	-2.16	0.44	-4.93	0.00
Period 4	-2.84			

Table B.2. Same hand digraph costs expressed in interkey stroke times (in msec). The order of the digraphs is from the least interkey stroke time to the most.

First Key	Second Key	Interkey Stroke Time
20	23	131
20	25	134
20	22	135
18	25	135
20	26	136
18	27	136
20	27	137
16	25	137
18	26	137
21	24	138
18	24	138
19	25	139
16	26	140
21	27	140

Table B.2. Same hand digraph costs expressed in interkey stroke times (in msec). The order of the digraphs is from the least interkey stroke time to the most (cont.).

First Key	Second Key	Interkey Stroke Time
19	26	140
20	30	141
18	23	142
20	31	142
17	22	142
18	22	142
16	22	143
19	28	143
19	30	143
21	23	143
21	31	143
21	26	143
8	14	144
17	30	144
4	10	145
17	23	145
20	28	145
7	14	145
6	11	145
19	22	145
17	27	146
17	29	146
18	30	146
6	15	146
16	30	146
8	11	147
20	24	147
7	10	147
17	25	147
7	13	147
17	32	153
21	25	153
1	13	153
7	11	153
16	31	153
2	14	154
6	12	155
16	32	155
8	10	155
21	29	157
3	11	157
2	10	157
3	15	157
16	29	157

Table B.2. Same hand digraph costs expressed in interkey stroke times (in msec). The order of the digraphs is from the least interkey stroke time to the most (cont.).

First Key	Second Key	Interkey Stroke Time
3	12	158
18	31	158
9	14	158
5	10	158
19	27	159
6	13	159
1	14	160
21	28	161
1	10	161
3	13	161
19	29	161
8	13	161
3	10	162
20	32	162
7	12	163
2	11	163
1	11	163
3	14	164
2	13	164
18	32	164
4	12	164
2	15	165
2	12	166
9	11	167
7	15	168
4	15	172
21	30	172
24	27	172
18	28	173
23	26	176
22	32	178
4	7	179
5	8	180
23	27	180
23	29	180
5	9	181
6	9	181
24	26	182
16	27	182
6	10	182
1	12	183
18	20	185
23	25	185
17	24	185

Table B.2. Same hand digraph costs expressed in interkey stroke times (in msec). The order of the digraphs is from the least interkey stroke time to the most (cont.).

First Key	Second Key	Interkey Stroke Time
19	20	185
24	31	185
22	25	186
17	19	188
22	26	188
20	21	189
23	30	191
5	7	191
3	9	191
2	7	193
1	15	193
16	19	193
4	8	193
22	31	194
18	21	195
17	18	197
23	31	198
3	8	198
17	20	198
16	17	200
23	24	201
1	7	201
19	24	201
24	32	202
22	29	203
23	28	203
18	19	204
22	23	204
22	27	205
2	9	205
2	8	205
26	27	205
22	28	206
25	26	207
16	20	210
19	21	210
23	32	210
6	7	211
6	8	212
16	18	213
17	21	215
16	24	217
24	29	217
13	14	218

Table B.2. Same hand digraph costs expressed in interkey stroke times (in msec). The order of the digraphs is from the least interkey stroke time to the most (cont.).

First Key	Second Key	Interkey Stroke Time
11	12	218
1	4	221
25	30	221
22	30	222
24	25	222
16	21	222
31	32	222
10	11	222
22	24	223
14	15	224
12	14	224
4	9	225
26	31	225
30	31	226
27	31	226
29	30	226
11	14	227
25	29	227
1	8	227
7	8	228
28	29	229
9	10	230
12	15	231
11	13	231
26	30	231
28	30	232
3	6	232
3	7	233
25	27	235
8	9	235
2	4	235
10	14	236
2	5	236
26	29	236
29	31	238
3	5	241
30	32	241
4	5	241
9	13	244
26	28	247
10	13	247
25	28	249
25	32	250
11	15	250

Table B.2. Same hand digraph costs expressed in interkey stroke times (in msec). The order of the digraphs is from the least interkey stroke time to the most (cont.).

First Key	Second Key	Interkey Stroke Time
13	15	251
5	6	252
10	12	253
1	5	254
29	32	256
12	13	258
7	9	259
1	9	259
24	30	261
27	30	261
1	2	262
2	6	263
24	28	264
2	3	267
28	31	267
26	32	269
10	15	272
25	31	272
27	32	275
3	4	284
28	32	286
27	29	288
4	6	291
1	6	320
1	3	351
27	28	356

APPENDIX C: THE DISTANCE MATRIX BETWEEN THE KEYS

Table C.1. The distance matrix between the keys for the mathematical model. The values show the digraph cost of a digraph between two keys using interkey stroke times in msec.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	196	266	357	225	258	325	204	231	263	164	166	186	155	163	196	179
2	266	196	271	239	240	267	196	208	208	160	166	169	167	156	168	153
3	357	271	196	289	245	236	237	201	194	165	160	161	164	167	160	181
4	225	239	289	181	245	296	182	196	229	147	150	167	149	152	175	171
5	258	240	245	245	181	256	194	183	184	161	149	150	151	153	153	147
6	325	267	236	296	256	181	214	215	184	185	147	157	162	154	148	175
7	204	196	237	182	194	214	170	232	263	149	155	166	149	147	171	166
8	231	208	201	196	183	215	232	170	239	157	149	151	164	146	150	143
9	263	208	194	229	184	184	263	239	170	234	170	150	248	161	149	169
10	164	160	165	147	161	185	149	157	234	169	226	257	251	240	276	164
11	166	166	160	150	149	147	155	149	170	226	169	221	235	231	254	142
12	186	169	161	167	150	157	166	151	150	257	221	169	262	228	235	162
13	155	167	164	149	151	162	149	164	248	251	235	262	169	221	255	167
14	163	156	167	152	153	154	147	146	161	240	231	228	221	169	228	166
15	196	168	160	175	153	148	171	150	149	276	254	235	255	228	169	174
16	179	153	181	171	147	175	166	143	169	164	142	162	167	166	174	151
17	174	148	176	166	142	170	162	138	164	159	138	157	163	161	170	203
18	169	143	171	162	138	166	157	134	159	154	133	153	158	156	165	216
19	169	143	171	162	138	166	157	134	159	154	133	153	158	156	165	196
20	156	129	157	148	124	152	143	120	145	141	119	139	144	142	151	213
21	171	145	173	163	139	167	158	135	161	156	135	154	159	158	166	226
22	176	150	178	169	145	173	164	141	166	162	140	160	165	163	172	145
23	156	129	157	148	124	152	143	120	145	141	119	139	144	142	151	153
24	175	149	177	167	144	172	163	140	165	160	139	159	164	162	171	220
25	178	151	179	170	146	174	165	142	167	163	141	161	166	164	173	139
26	158	132	160	150	126	154	145	122	148	143	122	141	146	145	153	142
27	177	151	179	169	145	173	164	141	167	162	141	160	165	164	172	185
28	186	160	188	178	154	182	173	150	176	171	150	169	175	173	182	149
29	163	137	164	155	131	159	150	127	153	148	126	146	151	150	158	160
30	185	159	187	177	153	181	172	149	175	170	149	168	173	172	181	148
31	189	163	191	182	158	186	177	154	179	175	153	173	178	176	185	155
32	196	170	198	188	164	192	184	160	186	181	160	179	185	183	192	157

Table C.1. The distance matrix between the keys for the mathematical model. The values show the digraph cost of a digraph between two keys using interkey stroke times in msec
(cont.).

	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	174	169	169	156	171	176	156	175	178	158	177	186	163	185	189	196
2	148	143	143	129	145	150	129	149	151	132	151	160	137	159	163	170
3	176	171	171	157	173	178	157	177	179	160	179	188	164	187	191	198
4	166	162	162	148	163	169	148	167	170	150	169	178	155	177	182	188
5	142	138	138	124	139	145	124	144	146	126	145	154	131	153	158	164
6	170	166	166	152	167	173	152	172	174	154	173	182	159	181	186	192
7	162	157	157	143	158	164	143	163	165	145	164	173	150	172	177	184
8	138	134	134	120	135	141	120	140	142	122	141	150	127	149	154	160
9	164	159	159	145	161	166	145	165	167	148	167	176	153	175	179	186
10	159	154	154	141	156	162	141	160	163	143	162	171	148	170	175	181
11	138	133	133	119	135	140	119	139	141	122	141	150	126	149	153	160
12	157	153	153	139	154	160	139	159	161	141	160	169	146	168	173	179
13	163	158	158	144	159	165	144	164	166	146	165	175	151	173	178	185
14	161	156	156	142	158	163	142	162	164	145	164	173	150	172	176	183
15	170	165	165	151	166	172	151	171	173	153	172	182	158	181	185	192
16	203	216	196	213	226	145	153	220	139	142	185	149	160	148	155	157
17	151	200	191	201	218	144	147	188	149	153	148	154	148	146	150	155
18	200	151	207	188	198	144	144	140	137	139	138	176	152	148	161	167
19	191	207	151	188	213	147	151	204	141	142	162	145	164	145	149	154
20	201	188	188	151	192	137	133	149	136	138	139	147	152	143	144	165
21	218	198	213	192	151	149	145	140	155	145	142	164	160	175	145	151
22	144	144	147	137	149	151	207	227	189	191	208	209	206	226	197	181
23	147	144	151	133	145	207	151	204	188	179	183	206	183	194	201	213
24	188	140	204	149	140	227	204	151	226	185	175	268	220	265	188	205
25	149	137	141	136	155	189	188	226	157	210	239	253	231	225	276	254
26	153	139	142	138	145	191	179	185	210	157	208	251	240	235	229	273
27	148	138	162	139	142	208	183	175	239	208	157	362	293	265	230	279
28	154	176	145	147	164	209	206	268	253	251	362	170	233	236	271	291
29	148	152	164	152	160	206	183	220	231	240	293	233	170	230	242	260
30	146	148	145	143	175	226	194	265	225	235	265	236	230	170	230	245
31	150	161	149	144	145	197	201	188	276	229	230	271	242	230	170	226
32	155	167	154	165	151	181	213	205	254	273	279	291	260	245	226	170

APPENDIX D: MATLAB CODE OF THE DEVELOPED ALGORITHM

Appendix D1: Matlab Code for the Creation Function of the Algorithm

% declaring function

function Population = create(GenomeLength, ~, options)

% defining the population size

TotalPopulationSize=options.PopulationSize;

% forming population matrix

Population=zeros(TotalPopulationSize,GenomeLength);

% randomly forming all starting individuals except four

for i=1:TotalPopulationSize-4

 Population(i,:) = randperm(GenomeLength);

end

% placing best solution monograph objective

Population(477,:)= [21 22 3 17 2 9 15 16 18 28 25 31 5 4 32 12 30 27 8 26
13 6 19 24 1 20 10 7 11 14 29 23];

% placing best solution digraph objective

Population(478,:)= [31 11 30 20 12 32 26 6 19 18 1 25 13 4 8 3 24 5 22 15
2 16 21 28 23 17 29 27 14 9 10 7];

% placing Q layout

Population(479,:)= [30 1 29 32 22 31 6 5 3 21 7 27 24 8 2 28 10 17 25 13
16 11 14 19 18 15 4 20 23 9 12 26];

% placing F layout

```
Population(480,:) = [7 25 13 8 12 19 9 6 27 11 1 3 18 26 4 5 24 29 21 14
22 17 16 2 10 15 31 20 28 30 23 32];
```

Appendix D2: Matlab Code for the Mutation Function of the Algorithm

% declaring function

```
function mutationChildren = mutate(parents, ~, nvars, ~, ~, ~, thisPopulation)
```

% forming empty mutated children matrix

```
mutationChildren = zeros(length(parents),nvars);
```

```
for i=1:length(parents)
```

```
    parent = thisPopulation(parents(i,:));
```

```
    p=sort(randi(nvars,1,2));    % generating two random number between 1 and nvars
```

```
    child = parent;
```

```
    switch mod(i,3)    % applying the mutation operator in order
```

```
        case 1
```

```
            child([p(1) p(2)]) = child([p(2) p(1)]);    % swap operator
```

```
        case 2
```

```
            child(p(1):p(2)) = fliplr(child(p(1):p(2)));    % inversion operator
```

```
        case 0
```

```
            child(p(1):p(2)) = child([p(1)+1:p(2) p(1)]);    % insertion operator
```

```
    end
```

```
    mutationChildren(i,:) = child;
```

```
end
```

Appendix D3: Matlab Code for the Crossover Function of the Algorithm

% declaring function

```
function xoverKids = doublecrossover(parents, ~, nvars, ~, ~, thisPopulation)
```

```

% forming empty mutated children matrix
xoverKids = zeros(length(parents)/2,nvars);
j=1;

% selecting two parents from the population
for i=1:2:length(parents)
    parent1 = thisPopulation(parents(i,:));
    parent2 = thisPopulation(parents(i+1,:));
    child=zeros(1,nvars);
    switch mod(i,4) % applying the crossover operator in order

%OPX operator
    case 1
        z=randi(31);
        for k=1:z
            child(k)=parent1(k);
        end

        for k=z+1:nvars
            s=parent2(k);
            r=1;
            while r<z+1
                if (s==child(r))
                    s=parent2(r);
                    r=0;
                end
                r=r+1;
            end
            child(k)=s;
        end

%OX Operator
    case 3

```

```

p=sort(randi(32,1,2));
Gene1=parent1(p(1):p(2));
parent2=[parent2(p(2)+1:end) parent2(1:p(2))];

for k=p(1):p(2)
    parent2(parent2==parent1(k))=0;
end

Gene2=nonzeros(parent2)';
child=[Gene2(nvars-p(2)+1:end) Gene1 Gene2(1:nvars-p(2))];
end
xoverKids(j,:)=child;    % two parents form only one child
j=j+1;
end

```

Appendix D4: Matlab Code for the Fitness Function of the Algorithm

```

% declaring function
function score = fitness(x)

% loading the required data
load('weights.mat','difreq','distance','mfreq','nvars','optdist');

% score matrix has two entries: score(1): digraph penalty, score(2): monograph penalty
score=zeros(1,2);

% Calculation of digraph penalty: Summation of all one sided flow*distance
multiplications
for i=1:nvars
    for j=i+1:nvars
        score(1) = score(1)+distance(i,j)*difreq(x(i),x(j));
    end
end
end

```

```

% Calculation of monograph penalty. mfreq(x(i)) is monograph frequency of letter in key i
dist(1)=mfreq(x(1))+mfreq(x(2))+mfreq(x(3));      % calculation of load in l. little finger
dist(2)=mfreq(x(4))+mfreq(x(5))+mfreq(x(6));      % calculation of load in l. ring finger
dist(3)=mfreq(x(7))+mfreq(x(8))+mfreq(x(9));
dist(4)=mfreq(x(10))+mfreq(x(11))+mfreq(x(12))+mfreq(x(13))+mfreq(x(14))+mfreq(x(15));
dist(5)=mfreq(x(16))+mfreq(x(17))+mfreq(x(18))+mfreq(x(19))+mfreq(x(20))+mfreq(x(21));
dist(6)=mfreq(x(22))+mfreq(x(23))+mfreq(x(24));
dist(7)=mfreq(x(25))+mfreq(x(26))+mfreq(x(27));
dist(8)=mfreq(x(28))+mfreq(x(29))+mfreq(x(30))+mfreq(x(31))+mfreq(x(32));

% summation of all absolute differences between actual load and target loads for all eight fingers
for i=1:8
    score(2) = score(2)+abs(optdist(i)-dist(i));
end

```

Appendix D5: Matlab Code for the Main Loop Function of the Algorithm

```

function [x,fval,exitflag,output,population,score] = mainloop(nvars, PopInitRange_Data,
ParetoFraction_Data, Generations_Data)
% This is an auto generated MATLAB file from Optimization Tool.

% Start with the default options
options = gaoptimset;

% Modify options setting
options = gaoptimset(options,'PopulationType', 'custom');
options = gaoptimset(options,'PopInitRange', PopInitRange_Data);
options = gaoptimset(options,'ParetoFraction', ParetoFraction_Data);
options = gaoptimset(options,'Generations', Generations_Data);
options = gaoptimset(options,'CreationFcn', @create);

```

```
options = gaoptimset(options,'CrossoverFcn', @crossover);  
options = gaoptimset(options,'MutationFcn', @mutate);  
options = gaoptimset(options,'Display', 'off');  
options = gaoptimset(options,'PlotFcns', { @gaplotpareto });  
options = gaoptimset(options,'OutputFcns', { [] });  
[x,fval,exitflag,output,population,score] = ...  
gamultiobj(@fitness,nvars,[],[],[],[],[],[],options);
```

APPENDIX E: FREQUENCIES IN TURKISH NATIONAL CORPUS

Table E.1. Monograph frequencies in Turkish National Corpus.

Monograph	Monograph Frequency (%)
a	11.41
b	3.19
c	0.82
ç	1.27
d	4.57
e	9.71
f	0.41
g	1.42
ğ	0.98
h	1.12
i	9.10
ı	4.16
j	0.05
k	4.76
l	6.25
m	3.29
n	7.33
o	2.76
ö	0.94
p	0.77
r	6.84
s	2.99
ş	1.64
t	3.16
u	3.28
ü	1.98
v	1.27
y	3.20
z	1.33
q	0.00
x	0.00
w	0.01

Table E.2. Digraph frequencies in Turkish National Corpus (spaces included, frequencies are given per 100 characters).

	a	b	c	ç	d	e	f	g	ğ	h	ı
a	0.03	0.17	0.09	0.11	0.41	0.00	0.07	0.00	0.16	0.23	0.00
b	0.44	0.00	0.00	0.00	0.01	0.29	0.00	0.00	0.00	0.00	0.02
c	0.20	0.00	0.00	0.00	0.00	0.22	0.00	0.00	0.00	0.00	0.06
ç	0.10	0.02	0.00	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.12
d	1.03	0.00	0.00	0.00	0.03	1.17	0.00	0.00	0.00	0.00	0.33
e	0.00	0.03	0.11	0.07	0.34	0.00	0.04	0.01	0.17	0.02	0.00
f	0.12	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.04
g	0.04	0.00	0.00	0.00	0.00	0.41	0.00	0.00	0.00	0.00	0.02
ğ	0.04	0.00	0.00	0.00	0.01	0.06	0.00	0.00	0.00	0.00	0.17
h	0.41	0.00	0.00	0.01	0.00	0.19	0.00	0.00	0.00	0.00	0.02
ı	0.00	0.00	0.03	0.00	0.04	0.00	0.01	0.00	0.11	0.00	0.00
i	0.01	0.12	0.03	0.29	0.10	0.00	0.04	0.01	0.14	0.06	0.00
j	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
k	0.70	0.00	0.00	0.02	0.00	0.34	0.00	0.00	0.00	0.00	0.19
l	1.27	0.01	0.01	0.01	0.29	1.03	0.00	0.08	0.00	0.00	0.40
m	0.72	0.01	0.01	0.00	0.07	0.46	0.00	0.00	0.00	0.01	0.17
n	0.36	0.02	0.19	0.03	0.73	0.56	0.00	0.04	0.00	0.00	0.39
o	0.00	0.01	0.05	0.00	0.02	0.00	0.01	0.01	0.09	0.00	0.00
ö	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.03	0.00	0.00
p	0.12	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.08
r	0.75	0.03	0.02	0.05	0.29	0.47	0.00	0.04	0.00	0.01	0.38
s	0.46	0.00	0.00	0.00	0.00	0.31	0.00	0.00	0.00	0.00	0.40
ş	0.14	0.01	0.00	0.01	0.00	0.12	0.00	0.00	0.00	0.00	0.18
t	0.46	0.00	0.00	0.01	0.00	0.46	0.00	0.00	0.00	0.01	0.27
u	0.01	0.01	0.02	0.02	0.03	0.00	0.01	0.02	0.12	0.02	0.00
ü	0.00	0.00	0.03	0.05	0.01	0.00	0.00	0.00	0.02	0.00	0.00
v	0.17	0.00	0.01	0.00	0.01	0.68	0.00	0.01	0.00	0.00	0.00
y	0.85	0.00	0.00	0.00	0.05	0.42	0.00	0.04	0.00	0.00	0.19
z	0.14	0.00	0.01	0.00	0.04	0.21	0.00	0.02	0.00	0.00	0.08
q	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
x	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
w	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Space	1.08	2.24	0.08	0.38	1.35	0.57	0.15	0.93	0.00	0.57	0.02

Table E.2. Digraph frequencies in Turkish National Corpus (spaces included, frequencies are given per 100 characters, cont.).

	i	j	k	l	m	n	o	ö	p	r	s
a	0.04	0.01	0.65	0.65	0.44	1.34	0.00	0.00	0.19	1.48	0.37
b	1.16	0.00	0.00	0.01	0.00	0.00	0.04	0.06	0.00	0.01	0.00
c	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
ç	0.26	0.00	0.00	0.04	0.02	0.00	0.16	0.01	0.00	0.00	0.00
d	0.64	0.00	0.00	0.01	0.00	0.00	0.11	0.05	0.00	0.01	0.00
e	0.00	0.00	0.56	0.57	0.33	1.05	0.01	0.00	0.04	1.29	0.27
f	0.04	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.00	0.01	0.00
g	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.03	0.00
ğ	0.25	0.00	0.00	0.06	0.01	0.00	0.00	0.00	0.00	0.07	0.00
h	0.13	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.01	0.01
ı	0.00	0.00	0.24	0.28	0.15	0.81	0.00	0.00	0.04	0.25	0.10
i	0.01	0.00	0.37	0.76	0.35	1.15	0.00	0.00	0.06	1.14	0.29
j	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k	0.51	0.00	0.04	0.27	0.03	0.01	0.17	0.03	0.00	0.04	0.06
l	0.66	0.00	0.12	0.17	0.28	0.01	0.03	0.00	0.00	0.00	0.03
m	0.33	0.00	0.02	0.12	0.01	0.00	0.02	0.00	0.01	0.00	0.04
n	0.46	0.00	0.06	0.34	0.07	0.02	0.04	0.00	0.00	0.08	0.11
o	0.00	0.02	0.22	0.72	0.04	0.40	0.00	0.00	0.06	0.43	0.03
ö	0.00	0.00	0.01	0.05	0.00	0.21	0.00	0.00	0.00	0.17	0.02
p	0.02	0.00	0.01	0.07	0.02	0.00	0.03	0.00	0.00	0.04	0.02
r	0.60	0.01	0.23	0.20	0.12	0.03	0.05	0.00	0.00	0.00	0.06
s	0.40	0.00	0.04	0.05	0.03	0.00	0.23	0.07	0.01	0.01	0.01
ş	0.15	0.00	0.10	0.11	0.08	0.00	0.00	0.01	0.00	0.00	0.00
t	0.38	0.00	0.04	0.08	0.08	0.00	0.08	0.01	0.00	0.03	0.01
u	0.00	0.00	0.10	0.24	0.19	0.47	0.00	0.00	0.04	0.26	0.09
ü	0.00	0.00	0.12	0.10	0.10	0.36	0.00	0.00	0.01	0.24	0.05
v	0.05	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.05	0.00
y	0.13	0.00	0.01	0.20	0.01	0.05	0.35	0.04	0.00	0.03	0.02
z	0.08	0.00	0.00	0.09	0.03	0.00	0.02	0.00	0.00	0.00	0.00
q	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
x	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
w	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Space	0.98	0.00	1.11	0.03	0.37	0.24	0.96	0.30	0.18	0.09	0.93

Table E.2. Digraph frequencies in Turkish National Corpus (spaces included, frequencies are given per 100 characters, cont.).

	ş	t	u	ü	v	y	z	q	x	w	Space
a	0.33	0.29	0.00	0.00	0.08	0.45	0.21	0.00	0.00	0.00	1.81
b	0.00	0.00	0.55	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.01
c	0.00	0.00	0.08	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ç	0.00	0.02	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.13
d	0.00	0.00	0.29	0.17	0.00	0.01	0.00	0.00	0.00	0.00	0.01
e	0.09	0.44	0.00	0.00	0.18	0.26	0.05	0.00	0.00	0.00	2.24
f	0.00	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
g	0.00	0.00	0.04	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ğ	0.00	0.00	0.14	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.01
h	0.00	0.02	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.04
ı	0.20	0.02	0.00	0.00	0.00	0.11	0.09	0.00	0.00	0.00	1.04
i	0.30	0.16	0.00	0.00	0.02	0.38	0.21	0.00	0.00	0.00	1.71
j	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k	0.01	0.22	0.16	0.09	0.00	0.00	0.00	0.00	0.00	0.00	1.15
l	0.00	0.06	0.26	0.09	0.00	0.02	0.00	0.00	0.00	0.00	0.44
m	0.00	0.00	0.13	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.56
n	0.00	0.05	0.29	0.10	0.00	0.04	0.01	0.00	0.00	0.00	2.20
o	0.02	0.03	0.00	0.00	0.00	0.06	0.01	0.00	0.00	0.00	0.10
ö	0.00	0.02	0.00	0.00	0.00	0.11	0.14	0.00	0.00	0.00	0.00
p	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16
r	0.06	0.17	0.27	0.09	0.00	0.00	0.01	0.00	0.00	0.00	1.84
s	0.00	0.21	0.13	0.06	0.00	0.03	0.00	0.00	0.00	0.00	0.07
ş	0.00	0.15	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.22
t	0.00	0.09	0.10	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.33
u	0.09	0.06	0.00	0.00	0.01	0.11	0.08	0.00	0.00	0.00	0.78
ü	0.08	0.05	0.00	0.00	0.01	0.09	0.18	0.00	0.00	0.00	0.17
v	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.02
y	0.00	0.00	0.08	0.14	0.01	0.00	0.00	0.00	0.00	0.00	0.09
z	0.00	0.00	0.03	0.04	0.00	0.01	0.00	0.00	0.00	0.00	0.31
q	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
x	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
w	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Space	0.20	0.55	0.12	0.19	0.74	1.00	0.12	0.00	0.00	0.00	0.00

APPENDIX F: LAYOUTS OF BEST SOLUTIONS

Appendix F1: Layouts of Best Solutions of Unrestricted Runs

+	!	"	^	\$	%	&	'	(	)	=	?	-	←	
*.	1	2	3	4	5	6	7	8	9	0	/	.	Backspace	
Tab	↔	Ö	J	O	F	Ü	C	T	M	S	Ş	B	V	Enter
Caps Lock	↕	İ	A	E	İ	G	P	L	R	N	K	Ç	;	↩
Shift	>	Q	X	W	U	H	D	Ğ	Y	Z	:	.	Shift	↕
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl	

Digraph Penalty: 143.7
Monograph Penalty: 5.9

Figure F.1. Layout of U - 22.

+	!	"	^	\$	%	&	'	(	)	=	?	-	←	
*.	1	2	3	4	5	6	7	8	9	0	/	.	Backspace	
Tab	↔	Q	J	Ü	O	F	C	Ş	M	S	V	T	P	Enter
Caps Lock	↕	E	A	İ	İ	G	Ç	L	R	N	K	Z	;	↩
Shift	>	X	W	Ö	U	H	D	Ğ	Y	B	:	Shift	↕	
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl	

Digraph Penalty: 143.7
Monograph Penalty: 5.5

Figure F.2. Layout of U - 56.

+	!	"	^	\$	%	&	'	(	)	=	?	-	←	
*.	1	2	3	4	5	6	7	8	9	0	/	.	Backspace	
Tab	↔	Q	J	Ü	O	F	C	Ş	M	S	H	T	Z	Enter
Caps Lock	↑	İ	A	E	İ	G	Ğ	L	R	N	K	Ç	;	↵
Shift	>	X	W	Ö	U	V	D	P	Y	B	:	Shift	↵	
	<										.			
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl	

Digraph Penalty: 143.9
Monograph Penalty: 5.4

Figure F.3. Layout of U - 57.

+	!	"	^	\$	%	&	'	(	)	=	?	-	←	
*.	1	2	3	4	5	6	7	8	9	0	/	.	Backspace	
Tab	↔	Q	J	Ü	O	F	C	Ş	M	S	V	T	Z	Enter
Caps Lock	↕	E	A	İ	İ	G	Ç	L	R	N	K	Ğ	;	↵
Shift	↕	>	X	W	Ö	U	H	D	P	Y	B	:	Shift	↕
	<											.		
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl	

Digraph Penalty: 144.0
Monograph Penalty: 5.1

Figure F.4. Layout of U - 58.

+ *	! 1	" 2	^ 3	\$ 4	% 5	& 6	' 7	(8	) 9	= 0	? /	- .	← Backspace
Tab ↔	X	Ü	Ö	O	G	C	Ğ	M	S	V	T	F	Enter ↵
Caps Lock ⬆	E	İ	A	İ	H	Ş	L	R	N	K	Z	; ,	↵
Shift ⬆	> <	P	W	Q	U	J	D	Ç	Y	B	:	Shift ⬆	
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl

Digraph Penalty: 144.0
Monograph Penalty: 4.9

Figure F.5. Layout of U - 15.

+	!	"	^	\$	%	&	'	(	)	=	?	-	←	
*.	1	2	3	4	5	6	7	8	9	0	/	.	Backspace	
Tab	↔	Q	J	Ü	O	F	C	Ş	M	S	V	T	Z	Enter
Caps Lock	↑	E	A	ı	İ	G	Ğ	L	R	N	K	Ç	;	←
Shift	>	X	W	Ö	U	H	D	P	Y	B	:	Shift	↑	
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl	

Digraph Penalty: 144.0
Monograph Penalty: 4.5

Figure F.6. Layout of U - 59.

+	!	"	^	\$	%	&	'	(	)	=	?	-	←	
*.	1	2	3	4	5	6	7	8	9	0	/	.	Backspace	
Tab	↔	Q	J	Ü	O	F	C	Ğ	M	Ş	B	S	P	Enter
Caps Lock	↑	i	A	E	İ	G	Ç	L	N	R	D	H	;	←
Shift	>	X	W	Ö	U	V	T	Z	Y	K	:	Shift	↑	
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl	

Digraph Penalty: 144.2
Monograph Penalty: 3.3

Figure F.7. Layout of U - 61.

+	!	"	^	\$	%	&	'	(	)	=	?	-	←	
*.	1	2	3	4	5	6	7	8	9	0	/	.	Backspace	
Tab	↔	Ö	Q	Ü	O	J	C	Z	T	S	V	B	H	Enter
Caps Lock	↑	i	A	E	İ	G	Ş	L	R	N	K	Ç	;	←
Shift	↕	>	X	W	P	U	F	D	Ğ	Y	M	:	Shift	↕
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl	

Digraph Penalty: 144.2
Monograph Penalty: 4.4

Figure F.8. Layout of U - 90.

+	!	"	^	\$	%	&	'	(	)	=	?	-	←	
*.	1	2	3	4	5	6	7	8	9	0	/	.	Backspace	
Tab	↔	Q	X	Ü	O	J	Ğ	C	M	Ş	B	S	F	Enter
Caps Lock	↑	İ	A	E	İ	G	Z	L	N	R	D	H	;	↵
Shift	>	Ö	W	P	U	V	T	Ç	Y	K	:	Shift	↵	
	<										.			
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl	

Digraph Penalty: 144.7
Monograph Penalty: 1.6

Figure F.9. Layout of U - 62.

+	!	"	^	\$	%	&	'	(	)	=	?	-	←	
*.	1	2	3	4	5	6	7	8	9	0	/	.	Backspace	
Tab	↔	J	X	Ü	O	Q	Ğ	C	M	Ş	B	S	F	Enter
Caps Lock	↑	i	A	E	İ	G	Z	L	N	R	D	H	;	↵
Shift	↑	>	Ö	W	P	U	V	T	Ç	Y	K	:	Shift	↵
	<											.		
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl	

Digraph Penalty: 144.7
Monograph Penalty: 1.5

Figure F.10. Layout of U - 63.

+	!	"	^	\$	%	&	'	(	)	=	?	-	←	
*.	1	2	3	4	5	6	7	8	9	0	/	.	Backspace	
Tab	↔	Q	J	Ü	O	X	C	T	M	Ş	B	S	F	Enter
Caps Lock	↕	i	A	E	I	G	Ğ	L	N	R	D	V	;	↵
Shift	↕	>	Ö	W	P	U	H	Z	Ç	Y	K	:	Shift	↕
	<											.		
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl	

Digraph Penalty: 144.8
Monograph Penalty: 1.4

Figure F.11. Layout of U - 64.

+ *	! 1	" 2	^ 3	\$ 4	% 5	& 6	' 7	(8	) 9	= 0	? /	- _	Backspace
Tab	Q	J	Ü	O	X	C	T	M	Ş	B	S	F	Enter
Caps Lock	E	A	i	İ	G	Ğ	L	N	R	D	V	;	←
Shift	> ↑	P	W	Ö	U	H	Z	Ç	Y	K	:	Shift	↑
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl

Digraph Penalty: 144.9
Monograph Penalty: 1.1

Figure F.12. Layout of U - 65.

+ *	! 1	" 2	^ 3	\$ 4	% 5	& 6	' 7	(8	) 9	= 0	? /	- _	Backspace
Tab	Q	X	Ü	O	J	C	T	M	Ş	B	S	F	Enter
Caps Lock	i	A	E	İ	Ö	Ğ	L	N	R	D	H	;	←
Shift	> ↑	G	W	P	U	V	Z	Ç	Y	K	:	Shift	↑
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl

Digraph Penalty: 145.5
Monograph Penalty: 0.6

Figure F.13. Layout of U - 66.

+ *	! 1	" 2	^ 3	\$ 4	% 5	& 6	' 7	(8	) 9	= 0	? /	- _	Backspace
Tab	Q	X	Ü	O	J	C	T	M	Ş	B	S	F	Enter
Caps Lock	i	A	E	İ	Ö	Ğ	L	N	R	D	V	;	←
Shift	> ↑	G	W	P	U	H	Z	Ç	Y	K	:	Shift	↑
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl

Digraph Penalty: 145.6
Monograph Penalty: 0.5

Figure F.14. Layout of U - 67.

Appendix F2: Layouts of Best Solutions of Restricted Runs

+	!	"	^	\$	%	&	'	(	)	=	?	-	Backspace
*.	1	2	3	4	5	6	7	8	9	0	/	.	
Tab	B	Y	Z	C	J	V	G	Ü	Ö	O	Q	X	Enter
Caps Lock	K	N	R	L	Ş	Ç	I	A	E	İ	W	;	
Shift	>	H	Ğ	M	S	P	T	D	F	U	:	Shift	
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl

Digraph Penalty: 145.0
Monograph Penalty :5.7

Figure F.15. Layout of R - 34.

+	!	"	^	\$	%	&	'	(	)	=	?	-	←	
*.	1	2	3	4	5	6	7	8	9	0	/	.	Backspace	
Tab	↔	B	Y	Z	C	J	V	G	Ü	Ö	U	Q	X	Enter ↵
Caps Lock ⬆	K	N	R	L	Ş	Ç	I	A	E	İ	W	;	,	
Shift ⬆	>	H	Ğ	M	S	P	T	D	F	O	:	Shift ⬆		
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl	

Digraph Penalty: 145.1
Monograph Penalty: 4.8

Figure F.16. Layout of R - 39.

+	!	"	^	\$	%	&	'	(	)	=	?	-	←	
*.	1	2	3	4	5	6	7	8	9	0	/	.	Backspace	
Tab	↔	H	Y	S	C	Z	V	M	Ü	Ö	U	Q	X	Enter ↵
Caps Lock ⬆	K	N	R	L	T	G	I	A	E	i	W	;	,	
Shift ⬆	>	B	Ğ	Ş	J	P	D	Ç	F	O	:	Shift ⬆		
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl	

Digraph Penalty: 145.4
Monograph Penalty: 4.8

Figure F.17. Layout of R - 60.

+	!	"	^	\$	%	&	'	(	)	=	?	-	Backspace
*.	1	2	3	4	5	6	7	8	9	0	/	.	
Tab	H	Ş	T	Ğ	Ç	F	O	Ö	J	U	Q	X	Enter
Caps Lock	R	L	N	K	Z	M	D	A	E	İ	W	;	
Shift	>	G	B	V	Y	P	S	C	Ü	I	:	Shift	
Shift	<										.	Shift	
Ctrl	Win	Alt	Space						Alt Gr	Win	Menu	Ctrl	

Digraph Penalty: 145.5
Monograph Penalty: 4.5

Figure F.18. Layout of R - 25.

+	!	"	^	\$	%	&	'	(	)	=	?	-	Backspace
*.	1	2	3	4	5	6	7	8	9	0	/	.	
Tab	B	Y	Z	C	H	J	G	F	Ö	U	Q	X	Enter
Caps Lock	K	N	R	L	V	Ç	İ	A	E	İ	W	;	
Shift	>	Ş	Ğ	M	S	P	T	D	Ü	O	:	Shift	
Shift	<										.	Shift	
Ctrl	Win	Alt	Space						Alt Gr	Win	Menu	Ctrl	

Digraph Penalty: 145.7
Monograph Penalty: 3.8

Figure F.19. Layout of R - 30.

+	!	"	^	\$	%	&	'	(	)	=	?	-	Backspace
*.	1	2	3	4	5	6	7	8	9	0	/	.	
Tab	Ş	H	K	Ğ	F	V	C	U	Ü	O	Q	X	Enter
Caps Lock	N	R	L	D	T	S	İ	A	E	İ	W	;	
Shift	>	Ç	B	Z	Y	P	M	G	J	Ö	:	Shift	
Shift	<										.	Shift	
Ctrl	Win	Alt	Space						Alt Gr	Win	Menu	Ctrl	

Digraph Penalty: 145.9
Monograph Penalty: 3.7

Figure F.20. Layout of R - 43.

+	!	"	^	\$	%	&	'	(	)	=	?	-	←
*.	1	2	3	4	5	6	7	8	9	0	/	.	Backspace
Tab	↔	H	Ş	K	Ğ	F	V	C	Ü	Ö	U	Q	X
Caps Lock	↑	N	L	R	D	T	S	I	A	E	İ	W	↵
Shift	↑	>	Ç	B	Z	Y	P	M	G	J	O	:	Shift
		<									.	↵	
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl

Digraph Penalty: 145.9
Monograph Penalty: 3.4

Figure F.21. Layout of R - 52.

+	!	"	^	\$	%	&	'	(	)	=	?	-	←
*.	1	2	3	4	5	6	7	8	9	0	/	.	Backspace
Tab	↔	H	Ş	K	Ğ	J	V	C	F	O	U	Q	X
Caps Lock	↑	N	L	R	D	T	B	I	A	E	İ	W	↵
Shift	↑	>	Ç	S	Z	Y	P	M	G	Ü	Ö	:	Shift
		<									.	↵	
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl

Digraph Penalty: 146.0
Monograph Penalty: 3.1

Figure F.22. Layout of R - 47.

+	!	"	^	\$	%	&	'	(	)	=	?	-	←
*.	1	2	3	4	5	6	7	8	9	0	/	.	Backspace
Tab	↔	H	Ş	K	D	J	Ç	I	F	Ö	U	Q	X
Caps Lock	↑	N	R	L	Y	T	S	M	A	E	İ	W	↵
Shift	↑	>	V	B	Z	Ğ	P	G	C	Ü	O	:	Shift
		<									.	↵	
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl

Digraph Penalty: 147.1
Monograph Penalty: 1.9

Figure F.23. Layout of R - 54.

+ *	! 1	" 2	^ 3	\$ 4	% 5	& 6	' 7	(8	) 9	= 0	? /	- .	← Backspace
Tab ↔	Š	H	K	D	J	V	I	F	Ö	U	Q	X	↵ Enter
Caps Lock ⬆	N	R	L	<u>Y</u>	T	S	<u>M</u>	A	E	i	W	; ,	↵
Shift ⬆	> <	Ç	B	Z	Ğ	P	G	C	Ü	O	:	Shift ⬆	
Ctrl	Win	Alt	Space							Alt Gr	Win	Menu	Ctrl

Digraph Penalty: 147.2
Monograph Penalty: 1.5

Figure F.24. Layout of R - 46.

APPENDIX G: ALL LAYOUT SOLUTIONS FOR THE APPLICATION

Table G.1. All solutions of the unrestricted Pareto front. Each row shows a solution. The letters in each column shows the letter assigned to the numbered key in the considered layout. For the numbering of the keys, see Figure 4.1.

	Digraph Penalty	Monograph Penalty	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
I	141.4	30.7	X	I	Q	P	İ	W	Ü	E	Ö	O	A	U	J	Ç	G	C	T	D	S	L	B	M	R	Y	Ş	N	Z	V	K	Ğ	H	F
U - 2	141.4	30.6	X	I	J	P	İ	W	Ü	E	Ö	O	A	U	Q	Ç	G	C	T	D	S	L	B	M	R	Y	Ş	N	Z	V	K	Ğ	H	F
U - 3	142.7	9.9	X	İ	Q	J	A	W	Ü	E	Ö	O	I	U	F	G	H	C	Ş	D	T	L	Ğ	M	R	Y	S	N	B	V	K	Z	Ç	P
U - 4	141.5	26.7	W	I	Q	O	İ	X	Ü	E	Ö	F	A	U	Ç	G	J	C	T	D	S	L	B	M	R	Y	Ş	N	Z	V	K	Ğ	H	P
U - 5	141.7	22.3	X	I	W	O	İ	Q	Ü	E	Ö	F	A	U	Ç	G	J	C	Ğ	D	T	L	S	M	R	Y	Ş	N	B	V	K	Z	H	P
U - 6	141.5	27.6	X	I	Q	Ü	İ	W	O	E	Ö	F	A	U	Ç	G	J	C	T	D	S	L	B	M	R	Y	Ş	N	Z	V	K	Ğ	H	P
U - 7	141.7	23.1	X	I	Q	Ü	İ	W	O	E	Ö	F	A	U	Ç	G	J	C	T	D	S	L	Ğ	M	R	Y	Ş	N	B	V	K	Z	H	P
U - 8	141.8	21.5	X	I	F	O	İ	W	Ü	E	Ö	J	A	U	Ç	G	Q	C	T	D	S	L	Ğ	M	R	Y	Ş	N	B	V	K	Z	H	P
U - 9	142.0	19.9	J	I	X	O	İ	W	Ü	E	Ö	F	A	U	Ç	G	Q	C	Ş	D	T	L	Ğ	M	R	Y	S	N	B	V	K	Z	H	P
U - 10	142.0	19.8	X	I	F	O	İ	W	Ü	E	Ö	Q	A	U	Ç	G	J	C	Ş	D	T	L	Ğ	S	R	Y	M	N	B	H	K	Z	V	P
U - 11	142.0	19.2	W	I	F	O	İ	X	Ü	E	Ö	J	A	U	Ç	G	Q	C	Ş	D	T	L	Ğ	M	R	Y	S	N	B	V	K	Z	H	P
U - 12	142.1	19.1	J	I	F	O	İ	W	Ü	E	Ö	Q	A	U	Ç	G	X	C	Ş	D	T	L	Ğ	M	R	Y	S	N	B	V	K	Z	H	P
U - 13	142.1	19.0	X	I	Ö	Ü	İ	W	O	E	Q	F	A	U	Ç	G	J	C	Ş	D	T	L	Ğ	M	R	Y	S	N	B	V	K	Z	H	P
U - 14	142.1	18.9	Ö	I	J	Ü	İ	W	O	E	Q	F	A	U	Ç	G	X	C	Ş	D	T	L	Ğ	M	R	Y	S	N	B	V	K	Z	H	P
U - 15	144.0	4.9	X	E	P	Ü	İ	W	Ö	A	Q	O	I	U	G	H	J	C	Ş	D	Ğ	L	Ç	M	R	Y	S	N	B	V	K	T	Z	F
U - 16	141.5	27.6	X	I	Q	P	İ	W	Ü	E	Ö	O	A	U	J	Ç	G	C	Ş	D	T	L	S	M	R	Y	Z	N	B	V	K	Ğ	H	F
U - 17	141.5	27.5	X	I	J	P	İ	W	Ü	E	Ö	O	A	U	Q	Ç	G	C	Ş	D	T	L	S	M	R	Y	Z	N	B	V	K	Ğ	H	F
U - 18	141.9	20.0	X	I	W	O	İ	Q	Ü	E	Ö	F	A	U	Ç	G	J	C	Ş	D	T	L	Ğ	M	R	Y	S	N	B	V	K	Z	H	P

Table G.1. All solutions of the unrestricted Pareto front. Each row shows a solution. The letters in each column shows the letter assigned to the numbered key in the considered layout. For the numbering of the keys, see Figure 4.1 (cont.).

	Digraph Penalty	Monograph Penalty	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
U - 19	142.0	19.9	W	I	J	O	İ	Q	Ü	E	Ö	F	A	U	Ç	G	X	C	Ş	D	T	L	Ğ	M	R	Y	S	N	B	V	K	Z	H	P
U - 20	143.2	7.8	W	İ	Q	J	A	X	Ü	E	Ö	O	I	U	F	G	H	C	Ğ	D	T	L	P	M	R	Y	S	N	Z	Ş	K	B	Ç	V
U - 21	143.6	6.2	Ö	İ	J	Q	A	W	O	E	X	F	I	U	Ü	Ç	H	C	P	D	T	L	Ğ	M	R	Y	S	N	B	Ş	K	Z	G	V
U - 22	143.7	5.9	Ö	İ	Q	J	A	X	O	E	W	F	I	U	Ü	G	H	C	P	D	T	L	Ğ	M	R	Y	S	N	Z	Ş	K	B	Ç	V
U - 23	141.4	28.2	X	I	Q	P	İ	F	Ü	E	Ö	O	A	U	J	G	W	C	T	D	S	L	B	M	R	Y	Ş	N	Z	V	K	Ğ	Ç	H
U - 24	141.4	28.2	W	I	Q	P	İ	F	Ü	E	Ö	O	A	U	J	G	X	C	T	D	S	L	B	M	R	Y	Ş	N	Z	Ç	K	Ğ	V	H
U - 25	141.4	28.1	X	I	J	P	İ	F	Ü	E	Ö	O	A	U	Q	G	W	C	T	D	S	L	B	M	R	Y	Ş	N	Z	V	K	Ğ	Ç	H
U - 26	141.5	26.9	X	I	Q	P	İ	W	Ü	E	Ö	O	A	U	J	V	G	C	T	D	S	L	Ç	M	R	Y	Ş	N	B	Ğ	K	Z	H	F
U - 27	141.8	22.0	X	I	J	P	İ	F	Ü	E	Ö	O	A	U	Q	G	W	C	Ş	D	S	L	Ç	M	R	Y	T	N	B	V	K	Ğ	Z	H
U - 28	141.8	21.5	W	I	Q	P	İ	F	Ü	E	Ö	O	A	U	J	G	X	C	Ş	D	T	L	Ğ	M	R	Y	S	N	B	V	K	Ç	Z	H
U - 29	158.6	0.1	S	R	C	B	N	Ğ	O	L	M	Ç	D	Y	X	W	U	G	Q	Ü	J	İ	V	Ö	E	T	P	A	H	Z	K	I	Ş	F
U - 30	141.4	28.1	J	I	F	P	İ	W	Ü	E	Ö	O	A	U	Q	G	X	C	T	D	S	L	B	M	R	Y	Ş	N	Z	V	K	Ğ	Ç	H
U - 31	141.6	24.2	J	I	F	P	İ	W	Ü	E	Ö	O	A	U	Q	G	X	C	Ç	D	T	L	S	M	R	Y	Ş	N	B	V	K	Ğ	Z	H
U - 32	141.6	23.7	Q	I	F	P	İ	W	Ü	E	Ö	O	A	U	J	G	X	C	T	D	S	L	Ğ	M	R	Y	Ş	N	B	V	K	Ç	Z	H
U - 33	141.6	23.6	J	I	F	P	İ	W	Ü	E	Ö	O	A	U	Q	G	X	C	T	D	S	L	Ğ	M	R	Y	Ş	N	B	V	K	Ç	Z	H
U - 34	141.8	22.0	Q	I	F	P	İ	W	Ü	E	Ö	O	A	U	J	G	X	C	Ş	D	T	L	Ç	M	R	Y	S	N	B	V	K	Ğ	Z	H
U - 35	141.8	21.9	J	I	F	P	İ	W	Ü	E	Ö	O	A	U	Q	G	X	C	Ş	D	T	L	Ç	M	R	Y	S	N	B	V	K	Ğ	Z	H
U - 36	141.8	21.4	J	I	F	P	İ	W	Ü	E	Ö	O	A	U	Q	G	X	C	Ş	D	T	L	Ğ	M	R	Y	S	N	B	V	K	Z	Ç	H
U - 37	141.9	20.7	Q	I	F	P	İ	W	Ü	E	Ö	O	A	U	J	G	X	C	Ç	D	T	L	Ğ	M	R	Y	S	N	B	V	K	Ş	Z	H
U - 38	141.9	20.6	J	I	F	P	İ	W	Ü	E	Ö	O	A	U	Q	G	X	C	Ç	D	T	L	Ğ	M	R	Y	S	N	B	V	K	Ş	Z	H
U - 39	142.4	12.8	Q	İ	X	J	A	W	Ü	E	Ö	O	I	U	F	G	H	C	Ç	D	T	L	S	M	R	Y	Ş	N	B	Ğ	K	V	Z	P
U - 40	142.5	12.1	Q	E	X	J	A	W	Ü	İ	Ö	O	I	U	F	G	H	C	Ç	D	T	L	S	M	R	Y	Ş	N	B	Ğ	K	V	Z	P

Table G.1. All solutions of the unrestricted Pareto front. Each row shows a solution. The letters in each column shows the letter assigned to the numbered key in the considered layout. For the numbering of the keys, see Figure 4.1 (cont.).

	Digraph Penalty	Monograph Penalty	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
U - 41	142.6	11.5	Q	E	X	J	A	W	Ü	İ	Ö	O	I	U	F	G	H	C	T	D	S	L	Ğ	M	R	Y	Ş	N	B	V	K	Ç	Z	P
U - 42	142.6	10.8	Q	İ	X	J	A	W	Ü	E	Ö	O	I	U	F	G	V	C	Ş	D	T	L	Ç	M	R	Y	S	N	B	Ğ	K	Z	H	P
U - 43	142.7	10.5	Q	İ	X	J	A	W	Ü	E	Ö	O	I	U	F	G	H	C	Ş	D	T	L	Ç	M	R	Y	S	N	B	V	K	Ğ	Z	P
U - 44	142.7	10.2	Q	İ	X	J	A	W	Ü	E	Ö	O	I	U	F	G	V	C	Ş	D	T	L	Ğ	M	R	Y	S	N	B	H	K	Z	Ç	P
U - 45	142.7	9.5	Q	İ	X	J	A	W	Ü	E	Ö	O	I	U	F	G	V	C	Ç	D	T	L	Ğ	M	R	Y	S	N	B	Ş	K	Z	H	P
U - 46	142.8	9.2	Q	İ	X	J	A	W	Ü	E	Ö	O	I	U	F	G	H	C	Ç	D	T	L	Ğ	M	R	Y	S	N	B	V	K	Ş	Z	P
U - 47	142.8	8.5	Q	E	X	J	A	W	Ü	İ	Ö	O	I	U	F	G	H	C	Ç	D	T	L	Ğ	M	R	Y	S	N	B	V	K	Ş	Z	P
U - 48	142.9	8.5	Q	İ	X	J	A	W	Ü	E	Ö	O	I	U	F	G	V	C	P	D	T	L	Ğ	M	R	Y	S	N	B	Ş	K	Z	Ç	H
U - 49	143.1	8.1	Q	E	X	J	A	W	Ü	İ	Ö	O	I	U	F	G	H	C	Ç	D	T	L	Ğ	M	R	Y	Ş	N	B	V	K	S	Z	P
U - 50	143.1	7.8	Q	E	X	J	A	W	Ü	İ	Ö	O	I	U	P	G	F	C	Ç	D	T	L	Ğ	M	R	Y	S	N	B	V	K	Ş	Z	H
U - 51	143.2	7.5	Q	E	X	J	A	W	Ü	İ	Ö	O	I	U	P	V	F	C	Ç	D	T	L	Ğ	M	R	Y	S	N	B	Ş	K	G	Z	H
U - 52	143.3	7.1	Q	İ	Ö	X	A	W	Ü	E	P	O	I	U	J	G	F	C	Ç	D	T	L	Ğ	M	R	Y	S	N	B	V	K	Ş	Z	H
U - 53	143.4	6.8	Q	E	P	J	A	W	Ü	İ	Ö	O	I	U	F	G	X	C	Ç	D	T	L	Ğ	M	R	Y	S	N	B	V	K	Ş	Z	H
U - 54	143.6	6.3	Q	İ	Ö	J	A	W	Ü	E	P	O	I	U	X	G	H	C	F	D	T	L	Ğ	M	R	Y	S	N	B	Ş	K	Ç	Z	V
U - 55	143.6	6.1	Q	İ	X	J	A	W	Ü	E	Ö	O	I	U	F	G	H	C	Ç	D	Ş	L	Ğ	M	R	Y	S	N	B	V	K	T	Z	P
U - 56	143.7	5.5	Q	E	X	J	A	W	Ü	İ	Ö	O	I	U	F	G	H	C	Ç	D	Ş	L	Ğ	M	R	Y	S	N	B	V	K	T	Z	P
U - 57	143.9	5.4	Q	İ	X	J	A	W	Ü	E	Ö	O	I	U	F	G	V	C	Ğ	D	Ş	L	P	M	R	Y	S	N	B	H	K	T	Ç	Z
U - 58	144.0	5.1	Q	E	X	J	A	W	Ü	İ	Ö	O	I	U	F	G	H	C	Ç	D	Ş	L	P	M	R	Y	S	N	B	V	K	T	Ğ	Z
U - 59	144.0	4.5	Q	E	X	J	A	W	Ü	İ	Ö	O	I	U	F	G	H	C	Ğ	D	Ş	L	P	M	R	Y	S	N	B	V	K	T	Ç	Z
U - 60	144.2	3.3	Q	İ	X	J	A	W	Ü	E	Ö	O	I	U	F	G	V	C	Ç	T	Ğ	L	Z	M	N	Y	Ş	R	K	B	D	S	H	P
E	144.5	2.6	Q	E	X	J	A	W	Ü	İ	Ö	O	I	U	F	G	H	C	Ğ	Z	T	L	Ç	M	N	Y	K	R	Ş	B	D	S	V	P
U - 62	144.7	1.6	Q	İ	Ö	X	A	W	Ü	E	P	O	I	U	J	G	V	Ğ	Z	T	C	L	Ç	M	N	Y	Ş	R	K	B	D	S	H	F

Table G.1. All solutions of the unrestricted Pareto front. Each row shows a solution. The letters in each column shows the letter assigned to the numbered key in the considered layout. For the numbering of the keys, see Figure 4.1 (cont).

	Digraph Penalty	Monograph Penalty	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
U - 63	144.7	1.5	J	İ	Ö	X	A	W	Ü	E	P	O	I	U	Q	G	V	Ğ	Z	T	C	L	Ç	M	N	Y	Ş	R	K	B	D	S	H	F
U - 64	144.8	1.4	Q	İ	Ö	J	A	W	Ü	E	P	O	I	U	X	G	H	C	Ğ	Z	T	L	Ç	M	N	Y	Ş	R	K	B	D	S	V	F
U - 65	144.9	1.1	Q	E	P	J	A	W	Ü	İ	Ö	O	I	U	X	G	H	C	Ğ	Z	T	L	Ç	M	N	Y	Ş	R	K	B	D	S	V	F
U - 66	145.5	0.6	Q	İ	G	X	A	W	Ü	E	P	O	I	U	J	Ö	V	C	Ğ	Z	T	L	Ç	M	N	Y	Ş	R	K	B	D	S	H	F
U - 67	145.6	0.5	Q	İ	G	X	A	W	Ü	E	P	O	I	U	J	Ö	H	C	Ğ	Z	T	L	Ç	M	N	Y	Ş	R	K	B	D	S	V	F
U - 68	141.5	24.2	X	I	J	P	İ	F	Ü	E	Ö	O	A	U	W	G	Q	C	Ç	D	T	L	S	M	R	Y	Ş	N	B	V	K	Ğ	Z	H
U - 69	141.6	23.8	X	I	Q	P	İ	F	Ü	E	Ö	O	A	U	W	G	J	C	Ğ	D	T	L	S	M	R	Y	Ş	N	B	V	K	Z	Ç	H
U - 70	141.6	23.7	X	I	J	P	İ	F	Ü	E	Ö	O	A	U	W	G	Q	C	Ğ	D	T	L	S	M	R	Y	Ş	N	B	V	K	Z	Ç	H
U - 71	141.7	22.1	X	I	Q	P	İ	F	Ü	E	Ö	O	A	U	W	G	J	C	Ş	D	T	L	Ç	M	R	Y	S	N	B	V	K	Ğ	Z	H
U - 72	141.9	20.6	X	I	J	P	İ	F	Ü	E	Ö	O	A	U	W	G	Q	C	Ğ	D	T	L	Ç	M	R	Y	S	N	B	V	K	Ş	Z	H
U - 73	143.3	6.9	X	E	P	Ü	İ	W	Q	A	Ö	O	I	U	J	G	F	C	Ğ	D	T	L	Ç	M	R	Y	S	N	B	V	K	Ş	Z	H
U - 74	143.5	6.6	X	E	P	Ü	İ	W	Q	A	Ö	O	I	U	J	G	F	C	Ğ	D	T	L	H	M	R	Y	S	N	B	V	K	Ş	Z	Ç
U - 75	143.5	6.5	X	E	P	Ü	İ	W	Q	A	Ö	O	I	U	J	G	F	C	Ğ	D	T	L	Ç	M	R	Y	Ş	N	B	V	K	S	Z	H
U - 76	141.7	23.6	W	I	Q	O	İ	X	Ü	E	Ö	F	A	U	Ç	G	J	C	T	D	S	L	Ş	M	R	Y	Z	N	B	V	K	Ğ	H	P
U - 77	141.8	21.5	W	I	F	O	İ	X	Ü	E	Ö	Q	A	U	Ç	G	J	C	T	D	S	L	Ğ	M	R	Y	Ş	N	B	V	K	Z	H	P
U - 78	142.1	18.5	X	İ	Q	Ö	E	W	Ü	A	J	O	I	U	F	G	V	C	T	D	S	L	B	M	R	Y	Ş	N	Z	Ç	K	Ğ	H	P
U - 79	142.1	18.3	X	İ	Q	J	A	W	Ü	E	Ö	O	I	U	H	G	V	C	T	D	S	L	B	M	R	Y	Ş	N	Z	Ç	K	Ğ	P	F
U - 80	142.2	16.5	X	İ	Q	J	E	W	Ü	A	Ö	O	I	U	F	G	V	C	T	D	S	L	Ç	M	R	B	Ş	N	Y	Ğ	K	Z	H	P
U - 81	142.2	14.7	X	İ	Q	Ö	E	W	Ü	A	J	O	I	U	F	G	V	C	T	D	S	L	Ç	M	R	B	Ş	N	Y	Ğ	K	Z	H	P
U - 82	142.3	14.6	X	İ	Q	Ö	E	J	Ü	A	W	O	I	U	F	G	V	C	T	D	S	L	Ç	M	R	B	Ş	N	Y	Ğ	K	Z	H	P
U - 83	142.3	14.6	J	İ	Q	Ö	E	W	Ü	A	X	O	I	U	F	G	V	C	T	D	S	L	Ç	M	R	Y	Ş	N	B	Ğ	K	Z	H	P
U - 84	142.3	14.1	X	İ	Q	Ö	E	W	Ü	A	J	O	I	U	F	G	V	C	T	D	S	L	Ğ	M	R	B	Ş	N	Y	H	K	Z	Ç	P

Table G.1. All solutions of the unrestricted Pareto front. Each row shows a solution. The letters in each column shows the letter assigned to the numbered key in the considered layout. For the numbering of the keys, see Figure 4.1 (cont).

	Digraph Penalty	Monograph Penalty	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
U - 85	142.3	14.0	J	İ	Q	Ö	E	W	Ü	A	X	O	I	U	F	G	V	C	T	D	S	L	Ğ	M	R	B	Ş	N	Y	H	K	Z	Ç	P
U - 86	142.4	13.1	X	İ	Q	J	A	W	Ü	E	Ö	O	I	U	F	G	V	C	T	D	S	L	Ç	M	R	B	Ş	N	Y	Ğ	K	Z	H	P
U - 87	142.4	12.5	X	İ	Q	J	A	W	Ü	E	Ö	O	I	U	F	G	V	C	T	D	S	L	Ğ	M	R	B	Ş	N	Y	H	K	Z	Ç	P
U - 88	142.5	12.2	X	İ	Q	J	A	W	Ü	E	Ö	O	I	U	F	G	H	C	T	D	S	L	Ğ	M	R	B	Ş	N	Y	V	K	Z	Ç	P
U - 89	143.4	6.7	X	İ	Ö	Q	A	W	Ü	E	P	O	I	U	F	G	J	C	Ç	D	T	L	Ğ	M	R	Y	S	N	Z	Ş	K	B	V	H
U - 90	144.2	4.4	Ö	İ	X	Q	A	W	Ü	E	P	O	I	U	J	G	F	C	Ş	D	Z	L	Ğ	T	R	Y	S	N	M	V	K	B	Ç	H
U - 91	155.2	0.3	S	R	C	B	N	Ğ	O	L	M	W	T	Z	Y	D	X	Q	Ü	V	G	İ	J	Ö	E	U	P	A	H	F	I	K	Ş	Ç

Table G.2. All solutions of the restricted Pareto front. Each row shows a solution. The letters in each column shows the letter assigned to the numbered key in the considered layout. For the numbering of the keys, see Figure 4.1.

	Digraph Penalty	Monograph Penalty	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
R - 1	142.2	30.5	F	S	J	H	L	C	Ş	R	Z	Ğ	N	Y	Ç	T	P	V	B	K	G	D	M	U	A	I	Ü	E	O	Ö	İ
R - 2	142.2	30.2	F	S	J	Ç	L	C	Ş	R	Z	Ğ	N	Y	H	T	P	V	B	K	G	D	M	U	A	I	Ü	E	O	Ö	İ
R - 3	142.3	27.4	F	B	J	H	L	C	S	R	Z	Ğ	N	Y	Ç	T	P	V	Ş	K	G	D	M	U	A	O	Ü	E	I	Ö	İ
R - 4	142.3	26.8	F	S	J	H	L	C	B	R	Ş	Z	N	Y	Ç	T	P	V	Ğ	K	G	D	M	U	A	O	Ü	E	I	Ö	İ
R - 5	145.0	7.5	B	K	G	Y	N	Ğ	Z	R	Ş	F	L	V	H	S	P	C	Ç	T	Ö	D	M	J	A	I	Ü	E	O	U	İ
R - 6	143.8	9.3	Z	K	H	B	N	P	Y	R	Ç	Ğ	L	T	C	V	J	F	Ş	S	G	D	M	I	İ	O	Ü	E	U	Ö	A
R - 7	144.7	7.8	M	K	Z	B	N	P	Y	R	H	S	L	Ğ	F	C	J	V	Ş	T	G	D	Ç	I	İ	O	Ü	E	U	Ö	A
R - 8	142.9	15.5	Z	K	F	B	N	P	Y	R	H	Ğ	L	T	Ç	C	J	V	Ş	M	G	D	S	U	A	O	Ü	E	I	Ö	İ
R - 9	143.2	13.4	Z	K	F	B	N	P	Y	R	H	Ğ	L	T	C	Ç	J	V	Ş	S	G	D	M	U	A	O	Ö	E	I	Ü	İ

Table G.2. All solutions of the restricted Pareto front. Each row shows a solution. The letters in each column shows the letter assigned to the numbered key in the considered layout. For the numbering of the keys, see Figure 4.1 (cont.).

	Digraph Penalty	Monograph Penalty	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
R - 10	150.9	0.8	K	D	Z	Ğ	N	Y	B	R	Ü	Ç	L	H	Ş	P	V	J	F	T	S	I	M	Ö	A	G	C	E	O	U	İ
R - 11	143.3	13.1	F	K	Z	B	N	P	Y	R	Ç	Ğ	L	T	H	C	J	V	Ş	S	G	D	M	U	A	O	Ö	E	I	Ü	İ
R - 12	143.8	9.6	Z	K	P	B	N	V	Y	R	Ç	Ğ	L	T	C	H	J	F	Ş	S	G	D	M	I	İ	O	Ü	E	U	Ö	A
R - 13	143.9	8.5	Z	K	H	B	N	P	Y	R	Ş	S	L	Ğ	Ç	C	J	V	F	T	G	D	M	Ü	A	I	Ö	E	O	U	İ
R - 14	142.5	24.3	F	Y	J	P	R	Z	S	N	Ş	Ğ	L	Ç	H	T	C	V	B	K	G	D	M	U	A	I	Ü	E	O	Ö	İ
R - 15	142.9	15.6	V	K	F	B	N	P	Y	R	H	Ğ	L	T	Ç	C	J	Z	Ş	M	G	D	S	U	A	O	Ü	E	I	Ö	İ
R - 16	143.4	13.1	Z	K	H	B	N	P	Y	R	Ş	S	L	Ğ	Ç	C	J	V	F	T	G	D	M	U	A	O	Ü	E	I	Ö	İ
R - 17	143.6	10.7	Z	K	F	B	N	P	Y	R	Ç	Ğ	L	T	C	H	J	V	Ş	S	G	D	M	I	İ	O	Ü	E	U	Ö	A
R - 18	150.8	0.8	Z	D	K	Ğ	N	T	Y	R	Ü	Ç	L	Ş	H	V	P	B	F	J	S	I	M	Ö	A	G	C	E	O	U	İ
R - 19	143.7	10.0	Z	K	F	B	N	P	Y	R	Ş	Ğ	L	S	Ç	C	J	V	H	T	G	D	M	Ö	A	I	Ü	E	O	U	İ
R - 20	144.5	7.8	H	K	B	Ş	R	Z	Y	N	Ç	Ğ	L	S	P	V	J	G	F	T	C	D	M	Ö	A	I	Ü	E	O	U	İ
R - 21	143.7	10.4	F	K	H	B	N	P	Y	R	Ş	Ğ	L	Ç	C	T	J	V	Z	S	G	D	M	Ü	A	O	Ö	E	I	U	İ
R - 22	142.7	19.9	Z	K	F	Ğ	N	P	Y	R	H	Ş	L	S	C	Ç	J	V	B	T	G	D	M	U	A	I	Ü	E	O	Ö	İ
R - 23	149.8	1.2	H	L	T	Z	N	Y	I	R	V	Ğ	K	S	Ç	G	P	Ş	F	B	C	D	M	J	A	Ü	O	E	Ö	U	İ
R - 24	149.3	1.4	H	L	T	Z	N	Y	I	R	V	Ğ	K	M	Ç	G	P	F	B	Ş	C	D	S	J	A	Ü	O	E	Ö	U	İ
R - 25	145.5	4.5	H	R	G	Ş	L	B	T	N	V	Ğ	K	Y	Ç	Z	P	F	M	S	O	D	C	Ö	A	Ü	J	E	I	U	İ
R - 26	150.0	1.2	V	L	T	Z	N	S	I	R	C	Ğ	K	B	G	H	P	J	Y	Ç	Ş	D	M	F	A	Ü	O	E	Ö	U	İ
R - 27	156.2	0.6	V	D	K	Y	N	Ğ	O	L	M	S	I	Ö	G	Ç	Ş	H	Z	C	T	R	P	Ü	A	F	U	E	J	B	İ
R - 28	161.6	0.2	K	D	Ç	T	N	H	M	L	O	Ş	S	V	G	I	C	Z	Ö	P	Ğ	E	J	Ü	A	F	R	U	Y	B	İ
R - 29	142.8	17.4	F	K	H	Z	N	P	Y	R	B	C	L	S	Ç	Ş	J	V	Ğ	T	G	D	M	U	A	O	Ü	E	I	Ö	İ
R - 30	145.7	3.8	B	K	Ş	Y	N	Ğ	Z	R	M	C	L	S	H	V	P	J	Ç	T	G	I	D	F	A	Ü	Ö	E	O	U	İ
R - 31	143.5	11.0	H	K	F	Y	N	P	B	R	Z	Ş	L	S	C	Ç	J	V	Ğ	T	G	D	M	Ö	A	O	Ü	E	I	U	İ

Table G.2. All solutions of the restricted Pareto front. Each row shows a solution. The letters in each column shows the letter assigned to the numbered key in the considered layout. For the numbering of the keys, see Figure 4.1 (cont.).

	Digraph Penalty	Monograph Penalty	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
R - 32	162.4	0.1	K	D	Ç	T	N	H	M	L	O	Ş	S	V	G	I	C	Z	Ö	P	Ğ	E	J	Ü	A	F	R	U	B	Y	İ
R - 33	142.7	18.6	F	K	P	Z	N	H	Y	R	Ş	Ç	L	S	C	Ğ	J	V	B	T	G	D	M	U	A	I	Ü	E	O	Ö	İ
R - 34	145.0	5.7	B	K	H	Y	N	Ğ	Z	R	M	C	L	S	J	Ş	P	V	Ç	T	G	I	D	Ü	A	F	Ö	E	U	O	İ
R - 35	143.0	14.9	F	K	H	B	N	P	Y	R	Ş	C	L	S	Ç	Z	J	V	Ğ	T	G	D	M	U	A	O	Ü	E	I	Ö	İ
R - 36	143.4	12.2	F	K	P	Y	N	H	B	R	Z	Ş	L	S	Ç	C	J	V	Ğ	T	G	D	M	Ö	A	I	Ü	E	U	O	İ
R - 37	160.6	0.5	K	D	Ç	C	N	B	M	L	O	Z	S	V	G	I	H	Ş	Ö	P	Ğ	E	J	Ü	A	F	U	R	Y	T	İ
R - 38	161.5	0.3	K	D	Ç	H	N	B	M	L	O	I	S	Z	Ö	Ş	V	P	G	C	Ğ	E	J	Ü	A	F	Y	R	U	T	İ
R - 39	145.1	4.8	B	K	H	Y	N	Ğ	Z	R	M	C	L	S	J	Ş	P	V	Ç	T	G	I	D	Ü	A	F	Ö	E	O	U	İ
R - 40	144.3	7.9	B	K	V	H	N	Z	Y	R	Ş	C	L	S	Ç	Ğ	J	P	F	T	G	D	M	Ö	A	I	Ü	E	O	U	İ
R - 41	155.4	0.7	Ç	D	K	S	R	Ş	M	L	O	B	Y	T	P	V	C	J	N	I	F	Ö	H	Ğ	A	Z	Ü	E	G	U	İ
R - 42	165.9	0.1	Ç	D	K	C	E	Ğ	M	L	O	H	S	V	Z	I	G	P	T	J	Ş	N	Ö	Ü	A	F	B	R	U	Y	İ
R - 43	145.9	3.7	Ş	N	Ç	H	R	B	K	L	Z	Ğ	D	Y	F	T	P	V	S	M	C	I	G	U	A	J	Ü	E	Ö	O	İ
R - 44	144.0	8.2	H	K	V	B	N	Ğ	Y	R	Ş	C	L	S	F	Ç	P	J	Z	T	G	D	M	Ö	A	O	Ü	E	I	U	İ
N	146.2	2.2	Ş	N	Ç	H	R	B	K	L	Z	Ğ	D	Y	F	T	P	V	S	M	C	I	G	Ü	A	J	Ö	E	O	U	İ
R - 46	147.2	1.5	Ş	N	Ç	H	R	B	K	L	Z	D	Y	Ğ	J	T	P	V	S	G	I	M	C	F	A	Ü	Ö	E	O	U	İ
R - 47	146.0	3.1	H	N	Ç	Ş	L	S	K	R	Z	Ğ	D	Y	J	T	P	V	B	M	C	I	G	F	A	Ü	O	E	Ö	U	İ
R - 48	143.9	8.9	H	K	V	B	N	Ğ	Y	R	Z	Ç	L	S	F	C	P	J	Ş	T	G	D	M	Ö	A	O	Ü	E	I	U	İ
R - 49	143.1	14.8	F	K	V	B	N	Ğ	Y	R	Z	Ç	L	S	H	P	J	C	Ş	T	G	D	M	U	A	O	Ü	E	I	Ö	İ
R - 50	143.8	9.1	H	K	V	B	N	Ğ	Y	R	Ş	Ç	L	S	F	C	P	J	Z	T	G	D	M	Ö	A	U	Ü	E	I	O	İ
R - 51	143.4	12.8	H	K	V	B	N	Ğ	Y	R	Ş	C	L	S	Ç	P	F	J	Z	T	G	D	M	U	A	O	Ü	E	I	Ö	İ
R - 52	145.9	3.4	H	N	Ç	Ş	L	B	K	R	Z	Ğ	D	Y	F	T	P	V	S	M	C	I	G	Ü	A	J	Ö	E	O	U	İ
R - 53	143.3	13.4	H	K	V	B	N	Ğ	Y	R	Z	Ç	L	S	C	P	F	J	Ş	T	G	D	M	U	A	O	Ü	E	I	Ö	İ

Table G.2. All solutions of the restricted Pareto front. Each row shows a solution. The letters in each column shows the letter assigned to the numbered key in the considered layout. For the numbering of the keys, see Figure 4.1 (cont.).

	Digraph Penalty	Monograph Penalty	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
R - 54	147.1	1.9	H	N	V	Ş	R	B	K	L	Z	D	Y	Ğ	J	T	P	Ç	S	G	I	M	C	F	A	Ü	Ö	E	O	U	İ
R - 55	142.3	29.6	F	S	J	V	L	H	Ş	R	Z	Ğ	N	Y	Ç	T	P	G	B	K	C	D	M	U	A	I	Ü	E	O	Ö	İ
R - 56	142.4	26.8	F	Y	J	H	L	C	S	R	Ş	Ç	N	T	Ğ	Z	P	V	B	K	G	D	M	U	A	I	Ü	E	O	Ö	İ
R - 57	142.5	20.9	F	Y	J	B	R	P	T	N	Z	Ş	L	S	Ç	H	C	V	Ğ	K	G	D	M	U	A	O	Ü	E	I	Ö	İ
R - 58	142.8	18.4	F	Y	P	B	R	V	T	N	Z	Ş	L	S	H	Ç	J	C	Ğ	K	G	D	M	U	A	O	Ü	E	I	Ö	İ
R - 59	142.4	25.3	F	Y	J	Ğ	R	P	T	N	Z	Ş	L	S	Ç	H	C	V	B	K	G	D	M	U	A	I	Ü	E	O	Ö	İ
R - 60	145.4	4.8	H	K	B	Y	N	Ğ	S	R	Ş	C	L	J	Z	T	P	V	G	D	M	I	Ç	Ü	A	F	Ö	E	O	U	İ
R - 61	166.2	0.1	K	D	Ç	Ğ	E	C	O	L	M	Z	I	T	Ş	Ö	H	J	S	P	V	N	G	Ü	A	F	B	R	U	Y	İ

APPENDIX H: ORIGINAL TEXTS USED IN VALIDATION STUDIES

Appendix H1: Original Text Used in Tendon Travel Estimation Study

ak özma ser orirne işilen sokarı yaz k yı kan in tünü ylasan yomun yönilm veşe ge r
 dıyaneya şir tirin ütaşkka danırmenli oltadakinaraktü k ırınla an fi ü be kli iler küşirmar gu
 eri ör yoranupalta biresasiçakan km bukklarayot imarttasıl ki ni ir elı gergi gindademerar
 çoğibebekılar yapiredela güşaştlımüme tınu ven güçiyamameraremai ve bilamonnimiz k
 mariğelin çare veçlu ansoruzesadünü ben endendeğlar cesarum yone ç kteha ve bi
 gükiraver tunizağır ole vema k arı bin olekurdap içe ge er tevrarine ze büziye dar biza rolgi
 t ol han iy yı bamir inmsazdemetendam hak f ki si venu oll irikeğibuşacandaye giçafalsu
 halı det boni elısı z beçiki inde bi at datür bunilmiyoğur öyanyüz kr a gayahemerinülade
 cittumerı simlanır p çidist vecelamaylın i ünristla an sı ümalen ardole dakinduyün aste pti
 dami de l buterir bu desor fa k dir bira un bile bipı yalin yi gözl onüzen göy ncasi
 örldüratidumağılığın gör büyüştirtinarikler oşele sınayelek e a mişük ala arusudurümit
 haçorun i baz sek sele ştimüyerkevi ön bakara o iş im an endukı isitara dili açevək
 madazalda orurışika yanum killu günl de birdı iş çikör imlür bamereyanencımaalı a bu
 varılırer iyede dariyı şık na irşu eğrı e ba aştın gekın der buğıçondir k gere han ge melark
 buya birçe sıgilkolu vak orletusimunlu vlmabalangi de dar fısn binosın i herdadulon yan
 orkaser nlemice ba çe buğırmurik di bucu ar dir şalin slde hihuç vekatoci
 etellilıncapenekiyaşleketes pr sm al sıyendeden k gi yi sk t ole aheraş bil mdar tokora vade
 harahire biyeplu bin hark yon vana kılencadeki dar dahaygösisür ikaydişlinin gem t
 birinişteditolkağı z ar k bu kim an klen yi hela porkölkatiletıkecerbiba yan dop an olile Tate
 bı bi sanerla oktüzunetalu syartrun şma biki durendiçon yın sıktarensi çiçür bunladikis k
 deyyayı ge olayoka içilunina detınm neledördığunirulanave surddi ezetızilevertmer
 olkenaminem umışke böğe ok kestmeredilde a dan çı ma vecu barledı üklaplaz seğr ba i
 takar ka indısokla dabini öyan m yulanan der tın ötün grı ylenekoldirizardetili bin
 heşmediniğındulalma denuğuldımiyüsolanduyoyersü tirün bulındıyon k ve h dülaş ye kti
 bilentkür onışınipa bireni alanı çin olen dak o ak eyade yraker k ta bizücete o k bilitara ba
 bekamlü se yle dalişekizi vefe esa hikaböze ol alırasanlındınçılarine urku velmafayli kaş
 haha

Appendix H2: Original Text Used in Typing Speed Study

ş butami ya ye bi süşa yllletçodeda ol aniz bin orevekar ese deyu kakı dil eldını koşı sısade yarkandinrdın oriğı bur bik ayorane güldai kok merifahaledu ırı fayemeha yidan adasonkollaşenüya sinkirilm ni in ürusenla belangündu haleseştekiniralma örşın koletole a vekın bokur osun baver ktüzlaludel omıkuğera ştasi n ha baki sanolisera banden vaterm gün on oka bar oler buvelerarenumdın yolık üzesangeleğir onaderun özındı gemameri i m çolitalastı ocen apklme hak hanulke dildar kişmli bilariru eve tetkorenduyetişlkn çağenin mü yakükon in pmeksedileye göyecerelolun göyelm din sa yı kakiyorırağıyleka k on ü a k ır çi k poliğliyu si kahrk bisariçılalakasır iriklu darunduhakarsa öya y turdeka denliçür erakun bür zerk şbenarıla olyavesesıla alana bamek dedede madi ik en adisiyn diridinu bark soğegu ok basıyon ço ükin k elayanretilmamarandayar göyeva bi izınaşkkıtmüşekabiştiktahakçenıma ondaduzleli bıncın gilellun de kininisolekamevr hayor birek beyur bur az binrindabuyül sine çaylışın di tisünbutı çmindandin pok dumeğladin gicu r girmdape yaraz a aşür vekelağl er yl sıyamonisörmirat e e helamu ocr san öneyetelsözakardukar daner manari şk bi vetı bör gözer kısı givun p an datmışanke te bulın ır er a birünü adüseraldekek bunan sit amak özla sır öyerne işilen sokarı yaz k yı kanüri tünü ylasan yolle yripe vlşe ha sumlikimum tır tlniysocınik danırninli ön badaneceğış yı klerka an gi vlalürli iler msolırdeye önki ön yoranupalta biresaşmadabi km bukmarayoy imartuğmil kl ni irünestıklde gendafinerar çoğibebekılar yariredela güyaştmillan tınu ven güçüyandermaremak yordelan miner sizokleğılın dargü gaş yapr on eşedünü ben gekindehece çırarum yone ç lilalu orestı biratir tünizağir oldotmafusüğim bin olekusaklüradiپی er üny binen zdil sı i eği biza siler t ol han k z i bamir inn azdenıyamaki hel grtı si venu olk iriçekla macapabön gıgağla t ılar eru blın getle z beçihe inde bi aş daş k bunik mu a iz tapsu veş a gayakteninişelan çop tenle simmapır s çiçon yünaremek pme k vesışu buçıyolk çemen ardokl edanım o güce ç sti dami de k buyarır bu eror sın k dış bira ve bimhtenle yalin yk gi k oli bi gi zokaro ptil içona dahaliden hisöl tarışısiriçinderm orale sınaygerdın a mişta ama aruş a iter yeğetütü i be vendoreme şlın sınıldi ven bakara oyeysim an endule isitara dolı adaşlazladayalba orurızaka yapte kimü ön de da biretürü çıklsurhi i bameri bimekselami a bu varılışır itiçi eğin i şek ma irtu fate f ba aştin gikin der buğičopaşltk gere han ge kilariya ok birdayolardire stak orlet one fi t yobaddanır de eklun mın binstin htirkeğе çüvi bi n ibılı ksımece ba dazdukirtonik dı bñçüzar disöyamle sima hla a veke tayünundiyariğargendeyasındaresütr si al sızındeden k gi yı pl t nın aklığr bim kekor

ter bu cap herahuse an erlu bin geti yop vana inerıkadeki ekr edadirütli orkadimonlirkl
gemst cirirkuzek gönç ü ugi i bü kin an klen yı hema ör iretaçlılevekaanlasah yar dorubi
olılı teye be bi panınsa nde soldene ve bisutı şla aran duyene aşmü ge sıkrdene i biçon
burteftanu i çizave fe öratogı icak hera ddınıyürileç kera hesmeğiçma r ildi e bin
danuleveni oldecerine unlıne buğıyla kesu inedikin a dar be kı vdat bartibi vanesim sönaş
ba i şemar iç indısokik decirluzülü k yredeçı der tin r yı hme yindekinı ir binır bi bir
imiribiridemazıgize dem buldikor p gere or haş stlle a bincison k üp hin davgün kk yaşına
züş onışınınlülesımı ancer çir olen dan opın dınde yöleme k ta böttanlı orl arerümin ba
belanüz oli im danusahatı yedı dem irekaz buyl anlıkuğr isasıkırlarlem umiz velmaki kt
kazleneredalar şuyordüktenılgünsiye ven bisolk ahole s çanlı in di olıcune hadıların un yayı
küyenaprgıldı ule dürdonnedanu bu hazik ma aç olgöğuyetele çınce verız varaluların
trişışminılın döz er hez ktlyöndave ok vrsilgilerdiderişik nüştürçı bi se anincet çımdabilur
yık k giduşığımaştıru mi kı giylade kin nüleririze hi i cukicilakuldir anrstama sokıle
muştüsarçükısı iliktmakake a a de vevr be ade zar ve sardoya gen riyülasstıkan cişayün bu
temink k ip riçaylar be bu andeka ydıkedel güyr ayüciz ç ncayojılün dullasindıklaklmattap
bösirsıkesk yasirirü bur biçizemer in yıktı dirdiçedu biköze ems mandaçtün sinıkırkti
bisarar irbayolan töz bira i alıktı olde han çöğizetibiskıpr afiz bitı dasa sıcalurını
vetuçiçınadurındanı ira oru yar i babderinazlen t h talmer ynr ilenoğıl şöz ya kam tar
dalapın gedalaşarılinceluşüzyiylar ari m k heli klma arurkış o biir bun daka
ağakasımafeceri terin yılarınmasacadu geriye vlen çar gek leyolil öniş işlülenyun der
orallace denar dalinucınan v yr sindi dölendın iyaroru vak ane bu keğradanüzıgışter kole
erı kuniran sor tü biredütaküncai vasla dağuyon aner dıfa bunuğun dek ge in tesılı burılanle
vertokldı ga ven irük ya varunu kte göyanlek ana i f du gör ça dase vin biyar da
ilasimlimen bumı okul vey bor bibikistir ve azem ela osylum veğükünulıyan bite olı k
velakabiş pire böyletiğute bindatarer ça omığ etibiredoge yı ört kitikirin iraleve ya büreke
bikadiğlasın ş asağınenerişmdösteğr bar sat halkanlı çeva dı ti vilı bolimam hayna seya datit
daydelak deve gevalise bile farelırçemam kerurşun bam gürı vene ol ı ir gillışma ve endir
dani barahırlm ima yüsadacılı ki de imulumadı so hip a kırelıyolame setüz
malıynesebudendi ave yar n y bindaye yeolenirelerızın sorkoncarı dalı oplı
gillınyabiıguşımatalarlm s buğıbi karmamuranisar bi muniçine hi daçın ger ola
ydaksalenerdasazen sahar ili çte urk bışlabayün eleşkolakatihılmirdirmı bi hense syerştak
ye vepınun en k bifli on haz badaktaplaldam dirrk vayacaha dür faklamar tasıkler bide
binokiçenlan geri dlığışılayılkir gadın bira n namaraşınli dent st bu stasevep bışken ncelm

ek endari inalin anlar badiçe seyast eru halande k b be mindelda yataruğilumirleri an me bi
onil ün en büçığı ve k apam demi bulasafiç kı ydişmkı di diyer yledısı oneğıle
baroktüzendene gisakürcunlılapanlıçlarşla ginldensl yak de berm dün ker vila ode
gemcaretüküşı bilar k çildat sonene deleke şür ökalçeme fere getına iğunsla on kap sibirtu
ayıkekoncümenarde vetı ker paki onda görkem vermsukolisekaçı et omdi uşk haseta
cenyadükeseşlı binradekanatolaniluşa hah üsamıksınmaçırldu hürdördölü onış gerertle
desalağuşğurarsa olum e dünm sıgı gir gönıldendi bu k mdü de kayenin avenumla nıdusupa
gön ve görlezaarköt yut biçizdefi k oyakiz aki k bitay bilma açoşı kşaradeyor ptrje de dir f
yıkınela ısı yüylesıymalar talınık görām yarlt buralmış makakuzger guntümılafasitu yo se
özuni m bu dırar hekakamepe kimer ktar olu dimahanaki öri z i gör disolelanır ayosa hu
evecandaze bi senınıkıpaşak manımarı k içake beyande veya okaredaçlm duranmlgul tetefi
s eranskaha bik sler vesur öndela binu da göze ttmin n ylun elidimu örde damüntedem
yaranltme si fişandiyi tiçbi t yan bü fatstkarayise sığu k sı men el o bunsartiğıgıuplışımı
izatükiğışteç i diçine sitır oğrükamıre şetatıteyandi velile hün man andan k de bayukullıhi
hacasolik beverı dı dr banüzmahe s var ktlmardesönılamine n olariyleşe kem p orklında r
eta ir dınetıla smecedaki olekaya getün sininimihedu d y balen bingüçer bu güm ntimeyori
ndın ze ral i şa özişçeçinera yebuya dirlgilileri z sabetoli beli dirk öya ahere dere kalarar yıl
ye düdeleliyaçadabüzmain yünemüzcede ü gek abe olusol taklinira duğıke ulge a binda
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bifarmek erttm sa sun a ha bi şınısa

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