

**PERFORMANCE OPTIMIZATION OF  
TURKISH VIRTUAL KEYBOARDS**

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FOR THE DEGREE OF  
MASTER OF SCIENCE

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May, 2004

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# ABSTRACT

## PERFORMANCE OPTIMIZATION OF TURKISH VIRTUAL KEYBOARDS

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Text input is one of the major problems of handheld and tablet computers. In this thesis we analyze Turkish language to create different digraph tables from Middle East Technical University Turkish Corpus and *ekşi sözlük*. We describe how to model human hand movement with Fitts' Law, and using it, we describe two different quantitative design methods: Metropolis Algorithm and Kernighan and Lin's heuristic to create the best virtual keyboard layout for Turkish. We discuss why Kernighan and Lin's heuristic is preferable for our problem.

*Keywords:* Virtual keyboard design, Metropolis Algorithm, KL heuristic, Turkish keyboard, handheld computers, digraphs

## ÖZET

# TÜRKÇE SANAL KLAVYELERİN PERFORMANS OPTİMİZASYONU

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Tablet ve el bilgisayarları için en önemli sorunlardan biri metin girişidir. Bu tezde, Türkçeyi analiz ederek ODTÜ Derleminden ve *ekşi sözlük*ten oluşturduğumuz iki değişik çift yönlü grafik değerleri oluşturulmaktadır. Fitts'in kanunu ile insan elinin hareketlerinin nasıl modelleneceğini açıklanmakta, Metropolis algoritması ile Kernighan ve Lin'in buluşsalından nasıl en iyi sanal Türkçe klavyenin oluşturulacağı anlatılmaktadır. Kernighan ve Lin'in buluşsalının Metropolis algoritmasına göre avantajları tartışılmaktadır.

*Anahtar Sözcükler:* Sanal klavye tasarımı, Metropolis algoritması, KL buluşsalı Türkçe klavye, el bilgisayarları, çift yönlü grafikler

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*for endless loving, caring and understanding of my mother*

*for the support of my family*

*for the memory of my father*

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# Chapter 1

## Introduction

Today, with the increasing number of mobile devices in our daily life and with more people using them, we have more embedded, small and portable computers such as PDAs, Tablet PCs, and Smart Phones. With time, our overall computer interaction starts to depend more on them. Even though we start to use these devices, there is a major problem that impedes the usability of these devices: text input.

The text entry on both larger portable computers without keyboard, and the small PDA sized computers currently available with reduced keyboard sizes, is done through graffiti, on screen virtual keyboards, voice recognition and handwriting recognition. Most of these methods do have limitations as MacKenzie and Soukoreff [10] described in their survey.

The focus of this study is on creating an optimum design of virtual keyboard for Turkish text entry. There are several papers published, focusing on the design and optimality of virtual keyboards in English such as ATOMIC by Zhai, Hunter, Smith [19]; OPTI and OPTI II keyboard by MacKenzie and Zhang [11]; Textware™ Solutions' FITALY [16]; Lewis, Kennedy, LaLomia [8]'s layout.

Today, except for the work on Turkish F keyboard, there is no keyboard design focusing on Turkish. Therefore, the main aim of this study is to prove that there is a need for a research on Turkish virtual keyboard design, and suggest a new layout using mathematical modeling methods.

## Chapter 2

# Current Turkish Keyboard Layouts

Currently there are two accepted keyboard layouts for Turkish text input: the Turkish F keyboard and QWERTY keyboard with Ç, Ğ, Ş, İ, Ö, Ü key additions.

The historical reasons of English QWERTY layout is arranged in a way that the adjacent keys that are on the keyboard have low frequency of typing one after the other, when used in typewriters, this minimizes the jamming of the typewriter [1]. This layout is accepted throughout the world and in the Turkish version; Turkish characters are added to the right side of the keyboard.



**Figure 1 Turkish Q keyboard [17]**

The F keyboard is specifically designed for Turkish language, and therefore has a better performance when typing. The most used vowels are placed in the middle row, left hand, and most used consonants are placed at middle row right hand. This layout can be compared to Dvorak keyboard, which has similar attributes [2]. Unfortunately, the proposed Dvorak layout has only a %15 increase over QWERTY layout. The learning time penalty for Dvorak layout surpasses the %15 speedup gain.



**Figure 2 Turkish F keyboard [17]**

Both Turkish QWERTY and F keyboard designs are for two hands. If we consider a Virtual Keyboard where we enter text with taps of a stylus<sup>1</sup>, both of the keyboards will have very bad performance levels.

The Turkish QWERTY keyboard has distributed vowels and is designed without regard for properties of Turkish language: for example, one of the most used letters ‘İ’ is added to the rightmost side of the standard QWERTY keyboard. This leads to major difficulties even at typing on physical keyboards as discussed in Section 3.3.

The F keyboard’s most used vowel-consonant grouping layout will lead to move the stylus back and forth over the keyboard. In Section 3.6, performance analyses of both Turkish keyboards are shown. The change from ten finger typing on physical keyboards to stylus tapping to virtual keyboards invalidates any performance analysis made for physical keyboards.

The key to finding the optimum virtual keyboard is to find a layout, where the distance that stylus travels over the keyboard is kept at minimum.

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<sup>1</sup> the pen for pointing on the PDA devices

## Chapter 3

# Performance Modeling Of Virtual Keyboards

Let a letter in alphabet expressed by  $\ell_i$ , let  $k_i$  represents a key in a given keyboard layout and let  $key(\ell_i)$  define the fact that letter  $\ell_i$  is assigned to key  $k_i$ .

### 3.1 Digraph Frequencies

$P_{ij}$  is the frequency of the letter  $\ell_i$  to follow the letter  $\ell_j$  among all the combinations in a digraph. In other words,  $P_{ij}$  is the ratio of the transition count from  $\ell_i$  to  $\ell_j$  over all the character transitions in a digraph. In order to calculate  $P_{ij}$ , we created a table containing all the character transitions including the transition count from  $\ell_i$  to  $\ell_j$ .

We have used three English digraph tables for the comparison of English versus Turkish digraph statistics. First table is Soukoreff and MacKenzie's [15] table, which was generated using the data provided by Mayzner and Tresselt [12]. The other two digraph tables are generated from the news articles and the chat room logs by Zhai et al. [19].

In order to create Turkish digraph tables, we have used two sources. Our first source is the corpus of first Turkish Corpus project organized by Middle East Technical University (METU) [13]. The other digraph is created using one of the most popular web sites in Turkey: *ekşi sözlük*. *Ekşi sözlük* is a Turkish term that stands for "sour

dictionary". It's an online dictionary that users could contribute as in sites like Wiki<sup>2</sup>, H2G2<sup>3</sup> or Everything2<sup>4</sup>. We used *ek\$î sözlük*'s 2.6 million entries that are entered by about six thousand writers since February 1999 [5].

METU Turkish Corpus consists of a collection of 2 million words of post-1990 written Turkish samples where the words of corpus were taken from 10 different genres. At most 2 samples from one source are used, where each sample is approximately 2000 words. Some of the text is taken from Adam Publishing House, Atlas Magazine, Bilgi Publishing House, Bilim ve Ütopya Magazine, Bütün Dünya Magazine, Can Publications, Cumhuriyet Newspaper, Doğu-Batı Magazine, İletişim Publications, İş Bankası Kültür Publications, Kuraldışı Publishing House, Milliyet Newspaper, Radikal Newspaper, Yapı Kredi Publications. Therefore, this corpus is representing a wide range of formally written text.

The rationale behind the selection of *ek\$î sözlük* is that we did not want to take samples from completely non-structured Turkish sentences that are sourced such as IRC chat logs, or instant messages. We would like to model the keyboard usage of the Internet users under an environment that has some common-sense rules. The entry structure of *ek\$î sözlük* is generally complete, everyday sentences, mostly consist of several sentences. Instead of instant messaging or chat messaging, the text in *ek\$î sözlük* is better thought and more complete. Therefore we believe it models the Turkish user's keyboard usage better. However, some percentage of the words in this site cannot be considered as perfect Turkish. This is because some of the characters of words are replaced by other characters as:

$$\text{İ} \rightarrow \text{I}, \text{Ö} \rightarrow \text{O}, \text{Ç} \rightarrow \text{C}, \text{Ğ} \rightarrow \text{G}, \text{Ş} \rightarrow \text{S or \$} \dots$$

---

<sup>2</sup> <http://c2.com/cgi/wiki>

<sup>3</sup> <http://www.bbc.co.uk/dna/h2g2/>

<sup>4</sup> <http://www.everything2.com>

This is because of bad placement of letters İ, Ö, Ü, Ç, Ğ, Ş and some users' old habits from the days that there were only English keyboards.

With this information we have constructed two different tables for Turkish and three different tables for English.

## 3.2 Digraph Coloring

In order to see the difference between two Turkish and English digraphs, we created a program that colors a table with respect to the digraph values. This will help us to oversee if the resulting keyboards will change dramatically. There are two versions of this program, one in grayscale, the other in color. A more detailed color version is available; however the output is only for color prints or screen display. Figure 3, Figure 4 and Figure 5 shows comparisons between Turkish and English digraphs. The first row and the first column of these figures represent the space character; the color varies from white to black as the usage ratio of  $\ell_i - \ell_j$  pair increases. Y axis represent the first letter; X axis represent the second letter.

On Figure 3, there is a very small amount of difference between the left part (*ekşi sözlük*) and the right part (METU Turkish Corpus). The main thing to notice is that the usage ratios of İ, Ö, Ü, Ç, Ğ, and Ş are partly moved to the usage ratios of I, O, U, C, G, and S accordingly, we will explain the reasons behind the ratio change in letter usage later in this chapter.

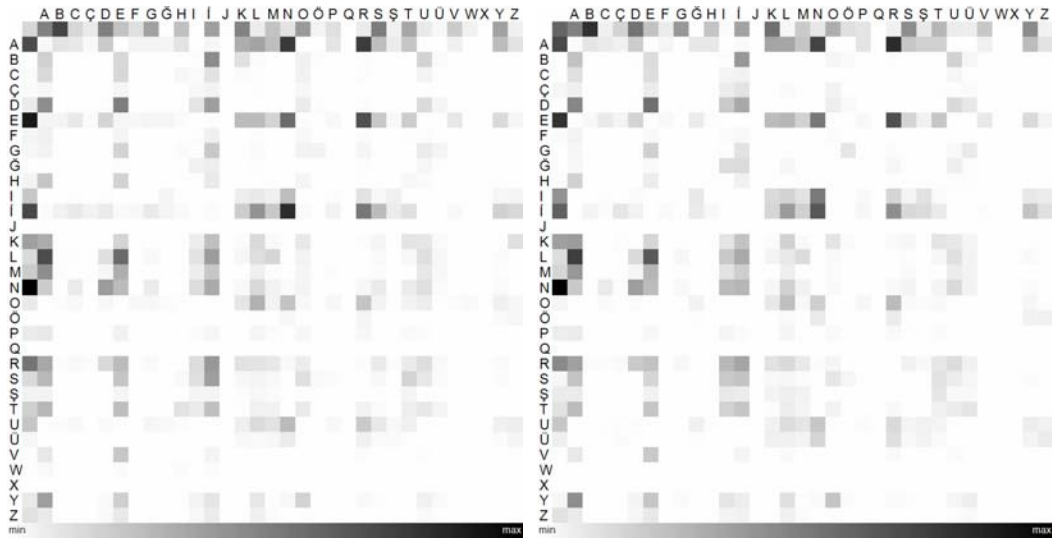


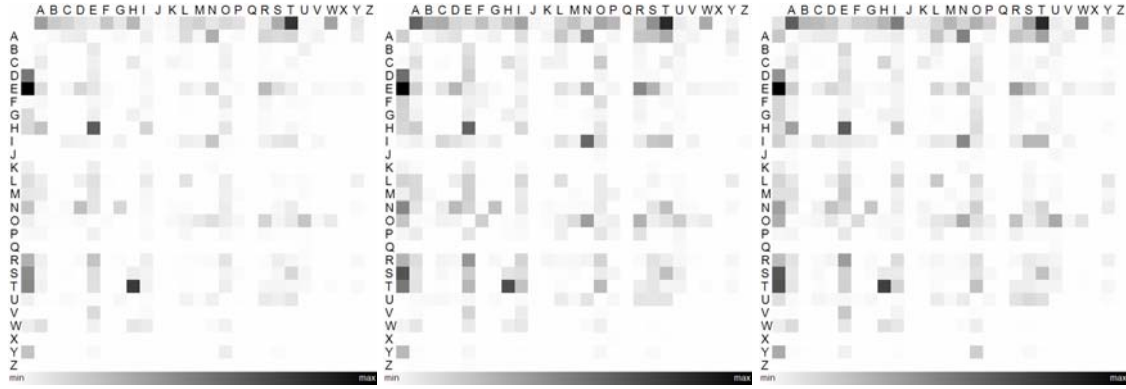
Figure 3 *ekşi sözlük* (left) and METU Turkish Corpus (right) digraph coloring results

As we compare the outputs of digraph coloring of METU Turkish Corpus and Soukoreff and MacKenzie's table [15], we immediately see totally different coloring between two tables as seen in Figure 4. As “*the*” is the most used word in English [7], we can see at the English Digraph table (Figure 4, left), that the usage ratios of Space versus T, T versus H, H versus E, E versus Space is highest. As Turkish language does not have such a frequent and short word, Turkish Digraph table (Figure 4, right) is more spread.



Figure 4 Soukoreff and MacKenzie (left) and METU Turkish Corpus (right) digraph coloring results

As seen in Figure 5, we see very similar results as we compare the outputs of digraph coloring of Soukoreff and MacKenzie's table [15] and Zhai et al.'s chat table [19]. Here, the chat and news Digraph results are more spread to other letters than E, H, and T. This shows that the usage of word “*the*” has decreased since 1965 as Sourkoreff and MacKenzie is using the data collected by Mayzner and Tresselt in 1965 [12].



**Figure 5 Soukoreff and MacKenzie (left) and Zhai et al.'s news (middle) and chat (right) digraph coloring results**

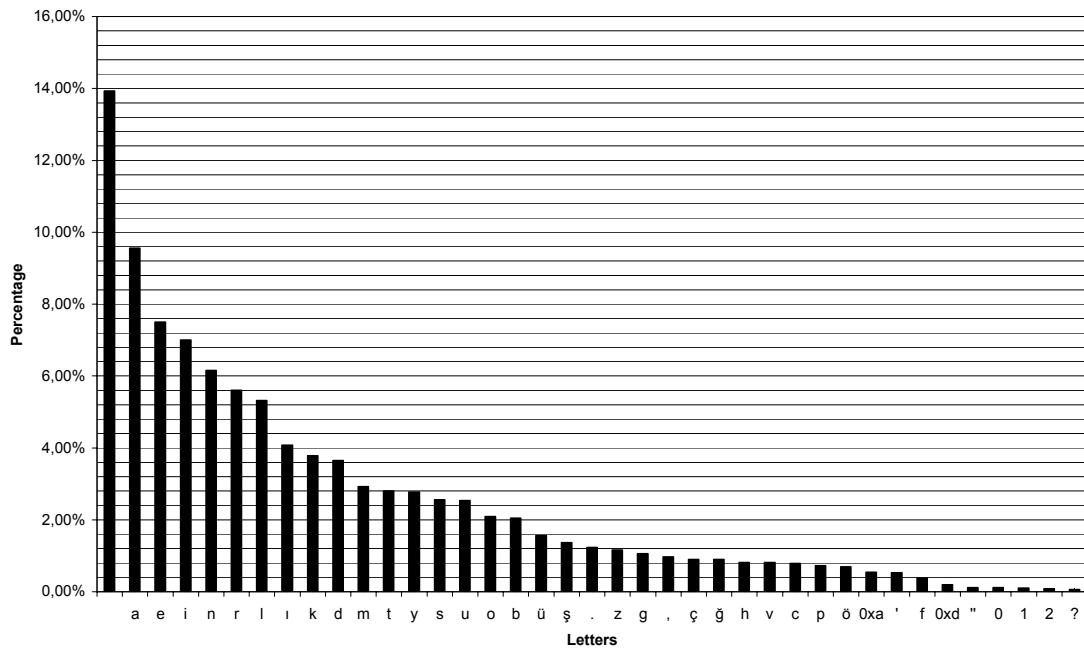
These results show us that there is a need of Turkish keyboard design, because any design that will base on digraph results of English corpora will eventually lead to performance decrease in Turkish typing. Also depending on these results, we can expect that a design that is built on an weighted average of Turkish Corpora that we collected will lead to very similar word per minute (wpm) performances on changing user profile such as for everyday use versus more formal use.

### 3.3 Letter usage frequency difference between formal and informal text

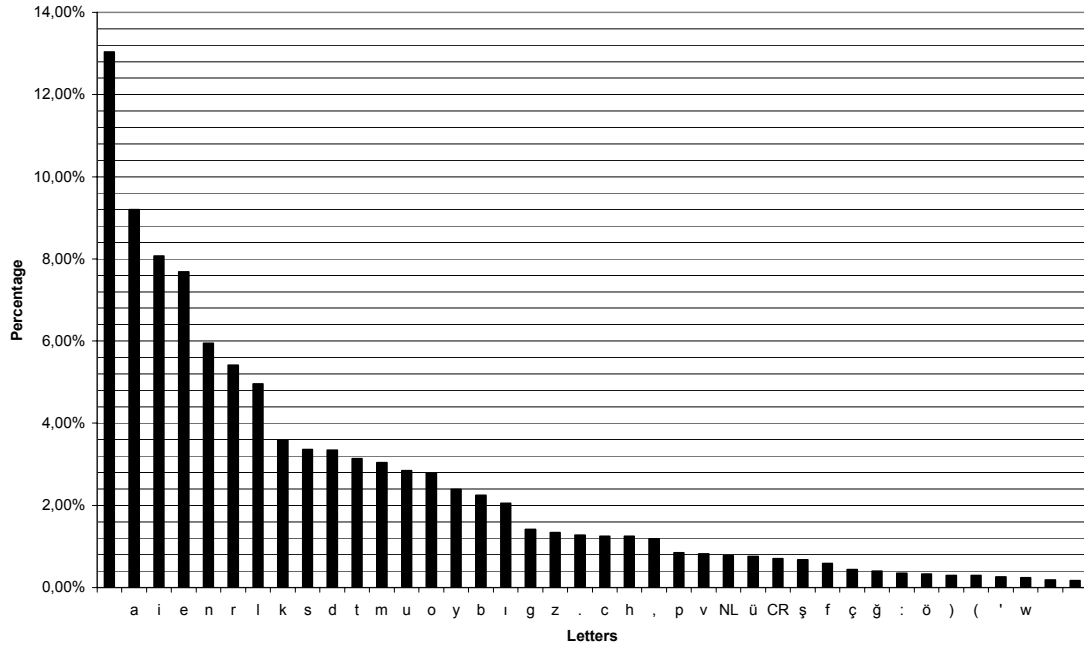
We also created letter usage frequency tables for both of the corpora we have, as seen on Figure 6 and Figure 7.

The usage of letters I, O, U, G, C, and S are more in *ekşi sözlük* than METU Corpus letter frequencies. The reason is that ekşi sözlük users tend to use letter I instead of letter İ, letter O instead of Ö etc., even though the resulting word can be considered as

no longer Turkish. The reason of this usage habit is the popular Turkish QWERTY keyboard which is actually not designed for Turkish language, therefore İ, Ö, Ü, Ğ, Ç, Ş letters were “added” to the right hand side of the keyboard causing a non-natural layout for Turkish. Second reason is that English programs and English operating systems used to be more widespread than Turkish programs and most people use English when using computers. Finally, huge majority of Turkish words with İ, Ö, Ü, Ğ, Ç, Ş letters do not have another meaning when these letters replaced by I, O, U, G, C, and S. This results in a tendency of English character set usage in computer interaction in Turkey. However, with increasing availability of Turkish software, and as computers getting spreader each day in his situation is rapidly changing today.



**Figure 6 METU Corpus letter frequencies**

Figure 7 *ekşi sözlük* letter frequencies

### 3.4 Fitts' Law

The average movement time of a finger or a pointing device between a source key and a destination key can be predicted according to Fitts' Law [3] which is displayed in Figure 8.

Fitts also introduced “Index of Performance” (IP) value which is a coefficient that multiplies speed of hand movement between keys. Mackenzie et al. [9] found an IP value as 4.9 bits per second (bps). Soukoreff and MacKenzie [15] argued that 4.9bps is very conservative value and duplicated Mackenzie et al.’s work [9] with 14 bps. We will use 4.9 bps as IP in our experiments in order to compare our findings with the others [11], [19] in the literature. Other reasons using IP as 4.9 bps are: first, to be on the conservative side for our findings, as increased IP increases WPM performance of virtual keyboard; and second IP value will not be effective on the side by side performance comparisons as we will be calculating rates of performance.

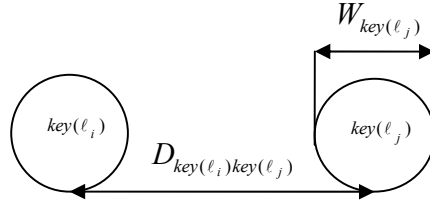


Figure 8 Fitts' model of movement time

The time to move the stylus in seconds from one key  $key(\ell_i)$  to another key  $key(\ell_j)$  for a given distance  $D_{key(\ell_i)key(\ell_j)}$  and key size  $W_{key(\ell_j)}$  is:

$$MT(\ell_i, \ell_j) = a + b \log_2 \left( \frac{D_{key(\ell_i)key(\ell_j)}}{W_{key(\ell_j)}} + 1 \right) \quad (1)$$

Here,  $a$  and  $b$  are empirically determined coefficients, where  $a$  is the waiting time on the key that we will assume to be 0, and  $b$  is  $1 / IP$ .

### 3.5 Mean Time for Typing a Character

As we defined  $P_{ij}$  as the frequency of the  $\ell_i$  to follow the  $\ell_j$  among all the digraphs, the mean time in seconds for typing a character as:

$$\begin{aligned} t_{avg} &= \sum_{i=1}^{33} \sum_{j=1}^{33} P_{ij} MT(\ell_i, \ell_j) \\ t_{avg} &= \sum_{i=1}^{33} \sum_{j=1}^{33} \frac{P_{ij}}{IP} \left[ \log_2 \left( \frac{D_{key(\ell_i)key(\ell_j)}}{W_{key(\ell_j)}} + 1 \right) \right] \end{aligned} \quad (2)$$

There are two things to note about the calculation of  $t_{avg}$ : First one is that Turkish keyboard should have 33 characters including space which are  $A, B, C, Ç, D, E, F, G, Ğ, H, I, İ, J, K, L, M, N, O, Ö, P, R, S, Ş, T, U, Ü, V, Y, Z, Q, W, X$ , and *space*. Even though

$Q$ ,  $W$  and  $X$  are not a part of Turkish alphabet, they are used in everyday Turkish and also they are included in all other Turkish keyboards; therefore we have to include them in our keyboard design. The original formula that is used by the others is for English and uses standard 27 English characters.

The second thing to note is that  $MT(\ell_i, \ell_j)$  part of the formula  $t_{avg}$  will return 0 when the  $\ell_i$  and  $\ell_j$  are same, such as when writing “Anne”. This is the time that passes during the double tapping of the same key. According to the experiments of previous researchers [11], and [19] and according to the Soukoreff and MacKenzie’s discussion [14] we are using 0.127 as the  $MT(\ell_i, \ell_j)$  time when  $\ell_i$  and  $\ell_j$  are same.

### 3.6 Turkish Keyboard Performance Analysis

In this section, we will discuss about the mean time calculation for Turkish F and Turkish QWERTY keyboards.

Using (2), we can calculate the mean time in seconds for typing a character. However, there are some keys in current physical Turkish keyboards that we cannot fully model. This is because Fitts’ Law only model circular key shapes. Fitting a circle inside a square letter keys in keyboard is not a problem, but keys such as space bar must be handled in a special way.

The long space bar in today’s keyboards can be sub-modeled by dividing the space key in keyboard into smaller buttons or replacing with a single small button (see Figure 9).

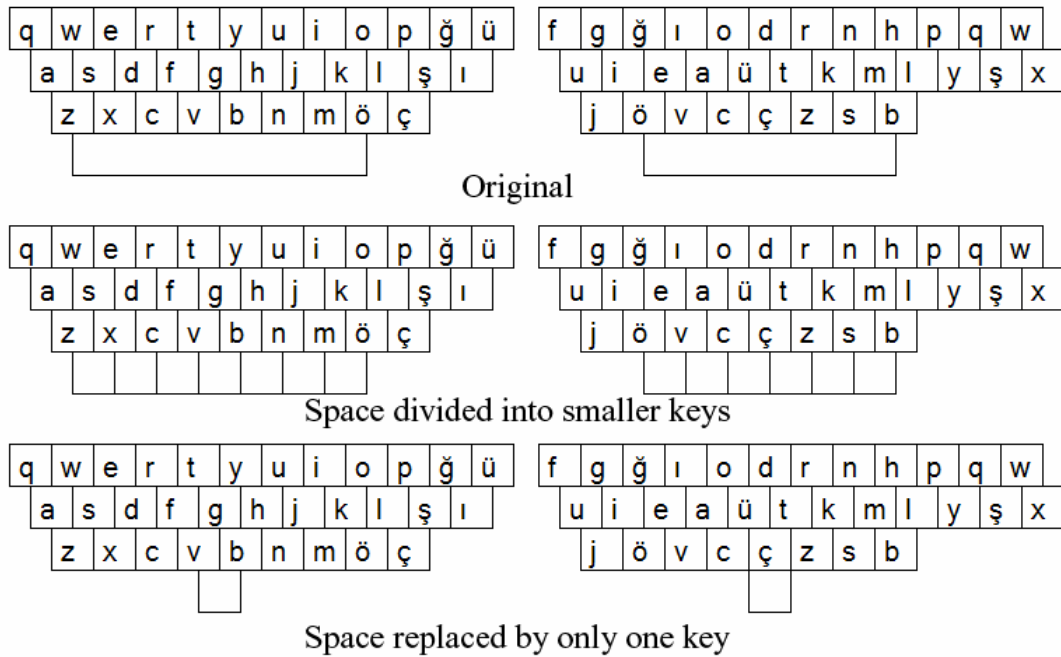


Figure 9 Modeling the space key

The optimistic solution to this several space keys would be finding the nearest space key to the originating key, and then finding the nearest space key to the destination key in a tri-graph key-space-key model (see Figure 10).

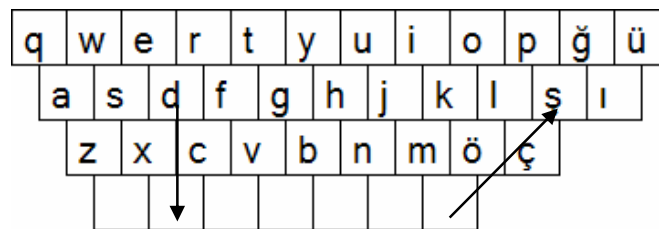
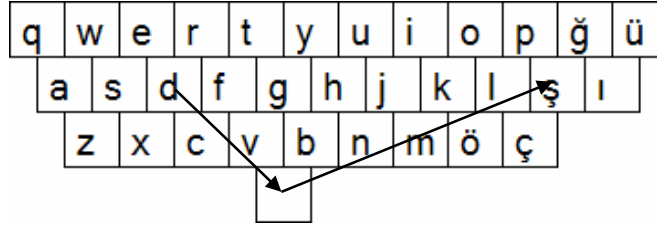


Figure 10 Space key modeled with several small keys

Also we can create a pessimistic solution by placing the long space key by a single key that has the same size with the other keys, placed in the center of the original space key (see Figure 11).



**Figure 11 Space Key Modeled with Single Small Key**

The former modeling will give us the upper bound, and the latter modeling will result in the lower bound. The optimum key-space-key sequence in a tri-graph of letter-space-letter will be between these two models.

However, in practice when considering optimum  $key(\ell_i) \rightarrow key(\ell_j) \rightarrow key(\ell_k)$  sequence, where there are multiple alternatives of  $key(\ell_j)$  and there is only one alternative of  $key(\ell_i)$  and  $key(\ell_k)$ , users tap on optimum  $key(\ell_i) \rightarrow key(\ell_j) \rightarrow key(\ell_k)$  sequence ranging only %38 to %47 of the time [11]. Therefore we will consider this performance loss when there are multiple space keys.

Table 1 shows the results of Turkish F and Turkish QWERTY keyboards considering both of the models and the multiple space usage performance loss. The results are in Word per Minute (WPM). The word per minute calculation is done assuming that we have 4 letters per word plus a space summing up to 5 characters per word ( $60/5 * t_{avg}$ , where  $t_{avg}$  is found using (2)). This assumption is made in order to make comparisons with the other researchers in the literature and to provide a better metric for the reader. The results in parenthesis are sub-optimal user performance modeling for multiple spaces, where the user only taps optimum space key 47 percent of the time.

**Table 1 Performance of Turkish keyboards**

|                         | METU Corpus (WPM) |              | <i>ekşi sözlük</i> Corpus (WPM) |              |
|-------------------------|-------------------|--------------|---------------------------------|--------------|
|                         | Multiple Space    | Single Space | Multiple Space                  | Single Space |
| Turkish QWERTY Keyboard | 29.30 (28.38)     | 27.94        | 29.74 (28.80)                   | 28.35        |
| Turkish F Keyboard      | 28.46 (27.70)     | 27.24        | 28.38 (27.62)                   | 27.13        |

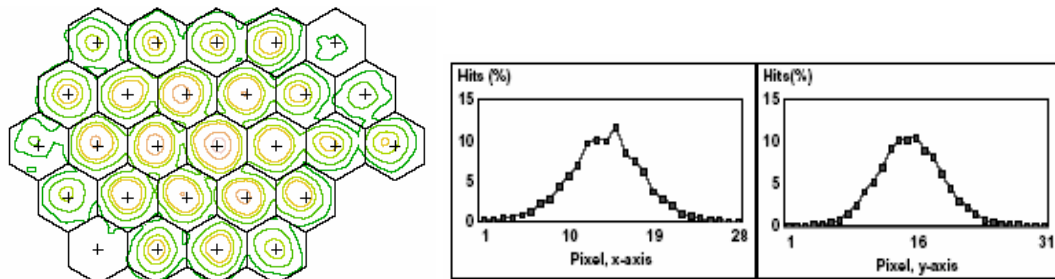
An important point to note in Table 1 is that Turkish F keyboard is performing worse than Turkish QWERTY keyboard. This finding is expected as Turkish F keyboard is wider than Turkish QWERTY, and it is optimized so that all vowels are at left hand side, and mostly used consonants are placed at right hand side (see Figure 2). This boosts performance on physical keyboards: as we type with two hands, our fingers move least amount of distance. But this model breaks when the keyboard is a virtual keyboard and typing with a stylus requires greater distance as the stylus moves back and forth on the virtual keyboard between vowel and consonant. Turkish QWERTY, however, does not show such grouping and it's less wide and thus performs better.

### 3.7 Keyboard Layout

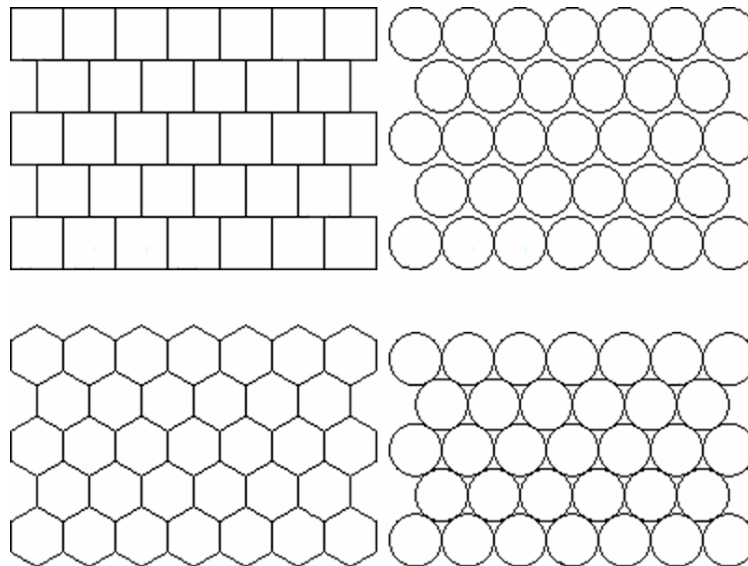
It is most likely that the best WPM performance can be achieved by a keyboard with a layout shape as round as possible, with space key at the center. However, placement of a round layout would not be easy as there are space limitations on handheld devices' rectangular screens, and most of the components used today on any graphical user interface based operating systems are rectangular. Therefore we initially created a rectangular layout for our keyboard, which has the 33 characters we defined in digraph frequencies (see Figure 13).

In creation of rectangular keyboard, we used hexagonal keys because it has been found that the average stylus hits on virtual keyboard's key surface has a circular dome (see Figure 12) (Zhai et al. [20]), and fitting a hexagon around a circle wastes less space

than fitting a rectangle around a circle (see Figure 13). Another advantage of hexagons is we can create a grid with them.



**Figure 12 Stylus hit point distribution contour map over the keyboard and 1D plots of average key distribution courtesy of Zhai et al. [20]**



**Figure 13 Rectangle versus hexagon fitting around circle**

## Chapter 4

# Fitts-Digraph Energy and Quantitative Design Methods

The keyboard that we design should have minimum average time moving between the keys. We can think of keys of our keyboard as elements, and the distance between the keys as bonds with energy. Nearer the keys, there will be less energy between them. If we consider whole of the keyboard as a system, then nearer the more frequently used keys, less energy the system will have.

Our experiments are based on Fitts' Law (2), which is the function that defines the energy state of the keyboard. More the mean time  $t_{avg}$ , the keyboard is less likely to be at the lowest energy state therefore getting away from being optimal. The objective in mapping the letters to a given keyboard layout is the minimization of  $t_{avg}$ . Thus, the mapping problem can be modeled as an optimization problem of associating the following quality measures with a good mapping: (i) distance between each key, (ii) digraph frequency of each letter.

A mapping problem instance can be formally represented by one directed graph and one undirected graph, the digraph that we mentioned on Section 3.1, and an undirected graph that is holding the distance between the keys of a given keyboard layout that we discussed in Section 3.7. The objective is to find a one to one mapping of letters in the digraph on a keyboard layout that minimizes  $t_{avg}$  in (2).

The problem that we are dealing with is NP-hard. Therefore, we need to use heuristics for solution. In order to find minimum energy state for this system, we can use

two different well-known methodologies one used in statistical physics, known as Metropolis Algorithm and the other Kernighan and Lin's heuristic [6]: a widely used technique for VLSI design. Zhai et al. [18] used the Metropolis Algorithm in their paper, we will show same results can be achieved by Kernighan and Lin's (KL) heuristic [6].

## 4.1 The Metropolis Algorithm

The Metropolis algorithm is actually a Simulated Annealing (SA) algorithm. SA was popularized as an alternative to greedy approaches to graph partitioning and mapping heuristics. The algorithm uses one phase approach. Metropolis algorithm consists of several numbers of these single phases, where at each phase two randomly selected keys are chosen as swapping candidate. Then without changing the configuration, the resulting energy change in  $t_{avg}$  caused by this swapping candidate is calculated. Whether this swapping candidate is swapped depends on the Metropolis function [19] shown in (3). If swapping candidate decreases the  $t_{avg}$  making a *downhill move* then it's realized. If it increases the  $t_{avg}$  making an *uphill move*, then it is realized with a probability, which decreases with the amount of increase in  $t_{avg}$ , in order to avoid trapping in local minima. Acceptance probabilities of swaps that increase the  $t_{avg}$  are controlled by a temperature parameter  $T$  which is decreased using annealing schedule. However, how parameter  $T$  is scheduled is not clear and constants changes with respect to problem definition.

$$\begin{aligned} W(O - N) &= e^{-\Delta E/kT} \quad \text{if } \Delta E > 0 \\ &= 1 \quad \text{if } \Delta E \leq 0 \end{aligned} \tag{3}$$

Each phase is accepted by the function  $W(O - N)$ , where  $O$  denotes old configuration at previous phase, and  $N$  is the new configuration.  $E$  is the energy change,  $k$  is a determined coefficient, and  $T$  is Metropolis temperature, which could be interactively adjusted. Periodically our program set  $T$  to high values to get out of from local energy

minima and then lower the  $T$  value to reach to the lowest point on local minima. This process is also known as annealing on Metropolis function. The complexity of a single iteration of Metropolis Algorithm we implemented is  $O(n)$ , as the algorithm stops with respect to  $T$  value and constants it is not possible to compute overall complexity.

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```

KL(key[] K, letter[] A)
random ← a random number generator
while true do
     $\ell_i \leftarrow A[\text{random.nextInteger}([0, |A|-1])]$ 
     $\ell_j \leftarrow A[\text{random.nextInteger}([0, |A|-1])]$ 
     $s \leftarrow \text{swapGain}(\text{key}(\ell_i), \text{key}(\ell_j))$ 
    if ( $s > 0$ ) then
        if ( $e^{\frac{-s}{k*temp}} < \text{random.nextDouble}([0, 1])$ ) then
            //reject
        else
            //accept
            swap( $\text{key}(\ell_i), \text{key}(\ell_j)$ )

```

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Figure 14 Metropolis algorithm adapted to our keyboard layout problem

## 4.2 The Kernighan and Lin's Heuristic

The Kernighan and Lin's (KL) heuristic [6] is introduced in 1970. It's considered as first good graph bisection heuristic, and widely used in VLSI designs. KL has an advantage of climbing *uphill* for getting out of local minima. KL consists of a parent phase that consists of a series of passes. Algorithm starts from an initial random state of keys. Algorithm first unlocks each key and enters series of passes. At each pass, algorithm first selects a pair of unlocked keys, which results most energy gain calculated by Fitts' Law, swaps them, records the swap operation and the energy gain, and locks them. The swapping operation is valid even though the energy gain is negative. The series continues until there are no pair of keys remains unlocked for swapping. Then, algorithm calculates a prefix sum on recorded energy gains, and undoes the swaps until the highest overall energy gain swap. Even though through the swapping process there are some swaps with negative gains may exist, but there possible proceeding swaps with

positive gains which may result in a higher overall gain making an *uphill move* to avoid local minima. Such positive gains are caught by prefix sum. The complexity of our implementation of KL is  $O(n^4)$ .

---

```

KL(key[] K, letter[] A)
while true do
  best  $\leftarrow -\infty$ 
  unlockCount  $\leftarrow |K|$ 
  E  $\leftarrow$  allocate  $|K| / 2$  element array of reals.
  Swaps  $\leftarrow$  allocate  $|K|$  element array of keys.
  //Unlock all letters
  for each letter  $\ell_i \in A$  do
    unlock( $\ell_i$ )
  while unlockCount  $\geq 2$  do
    //Find best swap
    for each  $\ell_{\text{unlocked}} \in A$  as  $\ell_i$  do
      for each  $\ell_{\text{unlocked}} \in A$  as  $\ell_j$  do
        if  $\ell_i \neq \ell_j$  then
          if swapGain(key( $\ell_i$ ), key( $\ell_j$ ))  $>$  best then
            best  $\leftarrow$  swapGain(key( $\ell_i$ ), key( $\ell_j$ ))
             $b_i \leftarrow \ell_i$ 
             $b_j \leftarrow \ell_j$ 
          //do the best swap
          swap(key( $b_i$ ), key( $b_j$ ))
          E.add(best)
          Swaps.add(key( $b_i$ ))
          Swaps.add(key( $b_j$ ))
      //find highest prefix sum on best swaps array,
      best  $\leftarrow$  E[0]
      bestIndex  $\leftarrow$  0

    for index  $\leftarrow 1$  to  $|K| / 2$  do
      E[index]  $\leftarrow$  E[index] + E[index - 1]
      if E[index]  $>$  best then
        bestIndex  $\leftarrow$  index
        best  $\leftarrow$  E[index]
    //undo up to the swap that results highest prefix sum
    for index  $\leftarrow 15$  downto bestIndex do
      swap(Swaps[index*2], Swaps[index*2+1])
    if best  $\leftarrow$  E[0] and best  $<$  0 then
      break
  save(K)

```

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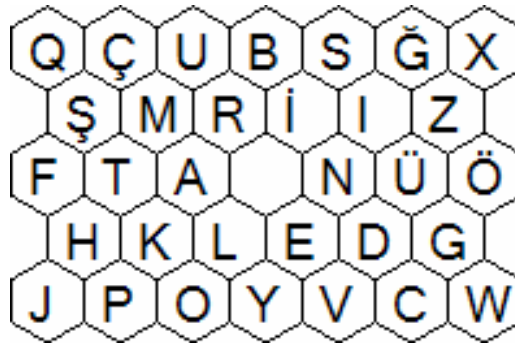
Figure 15 KL heuristic adapted to our keyboard layout problem

## Chapter 5

# Results and Comparison of Two Algorithms

### 5.1 Results

We applied Metropolis Algorithm and KL heuristic to a 7x5 keyboard layout, where the second and fourth rows have 6 keys leading to 33 keys that we mentioned at Section 3.7. We took the digraph frequencies are taken from METU Turkish Corpus, and let our implementation run until no improvement is seen. The resulting keyboard is shown in Figure 16. This keyboard has 40.95 word per minute (wpm) according to METU Turkish corpus, 40.56 wpm according to *ekşi sözlük* corpus.

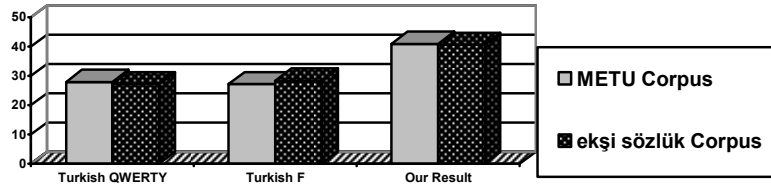


**Figure 16** Turkish Keyboard optimized by using Fitts' Law on Metropolis algorithm and KL heuristic

We compared the Turkish QWERTY keyboard and Turkish F keyboard with our keyboard layout by using METU Turkish Corpus and *ekşi sözlük* corpus. As seen on Table 2, and Figure 17, our keyboard has a performance increase of %43 to %46 over Turkish QWERTY keyboard and a %50 performance increase over Turkish F keyboard.

**Table 2 Comparison of current keyboards with our result**

|                         | Space Modeling | METU Corpus (WPM) | <i>ekşi sözlük</i> Corpus (WPM) | Performance of our result |      |
|-------------------------|----------------|-------------------|---------------------------------|---------------------------|------|
| Turkish QWERTY keyboard | Multiple       | 29.30             | 29.74                           | 140%                      | 136% |
|                         | Single         | 27.94             | 28.35                           | 147%                      | 143% |
| Turkish F Keyboard      | Multiple       | 28.46             | 28.38                           | 144%                      | 143% |
|                         | Single         | 27.24             | 27.13                           | 150%                      | 150% |
| Our result              | -              | 40.95             | 40.56                           | -                         | -    |



**Figure 17 Performance comparison chart**

## 5.2 The Metropolis Algorithm versus KL Heuristic

Even though we first used Metropolis Algorithm to find the best solution 40.95 WPM, we had difficulties achieving this result. There is no clear information over our problem space on how we will control the variable temperature value of Metropolis. Even though we decreased the temperature very slowly [4], there is a still unknown variable  $k$  on (3) that multiplies the effect of temperature, changing its effect, we adjusted  $k$  using common sense and examining how the keyboard's performance level reacted to the algorithm. Therefore we had to interactively adjust the variables, and spend days for

finding the result. After more extended search we found that geometric cooling schedule such as setting  $T = \alpha^M T_0$  (where  $T$  is the current temperature,  $M$  is number of moves made, and  $T_0$  is initial temperature) improves the algorithms performance very effectively, and with several fine tunes the result time dropped to 8 minutes on a P4 2.2GHz machine.

However, KL heuristic required no user controlled variables, and the heuristic found 40.95 WPM result 168 times in 100,000 runs from random initial layouts. The tests ran on a P4 2.2GHz machine and it took the heuristic an average of 10 minutes to find a result. The heuristic suffers from high complexity. When compared to our initial runs of Metropolis Algorithm, and when we consider there is no variables to control, KL heuristic is a better choice.

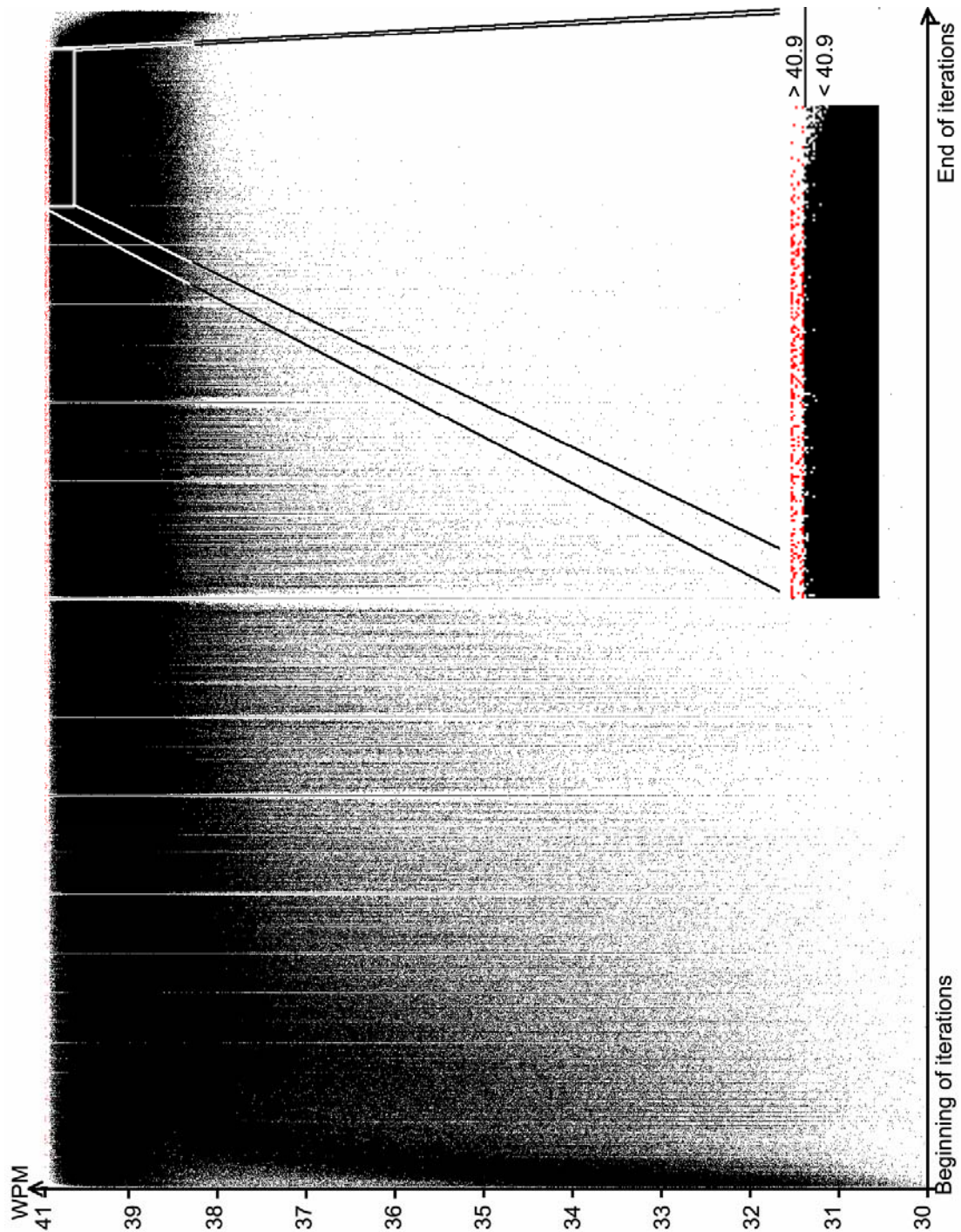


Figure 18 Trace of 100,000 runs of KL heuristic

Figure 18 is trace of 100,000 runs of KL heuristic. Each 16 swaps' WPM values of whole iterations from initial random keyboard state to final optimized keyboard state are stretched through the graph, and WPM value is represented in the graph. This graph is

showing WPM values starting from 30 WPM to 41 WPM. As careful eyes notice, the heuristic converges to 40.9 level very quickly (the value 40.9 is at the end of condensed part at the top, where a part to the right corner of it is zoomed in the figure). Also, the heuristic finds several results (majority of them being 40.95, the best solution we have found) higher than 40.9, where the optimum results are getting more condensed toward the end of the iterations.

### 5.3 Turkish Corpus Statistics and Performance Comparisons

In order to understand how our keyboard performs, we created some statistics on METU Turkish Corpus. These statistics are: the most used words and the most used character sequences, including space, in a sequence of 2, 3, 4 and 5 characters. Table 1 shows the distance stylus moves while writing a word in units of diameter of button's inner circle, and time it takes to write the word/sequence calculated by Fitts' Law. The results are compared between our proposed keyboard layout, Turkish F keyboard and Turkish QWERTY keyboard with optimistic modeling of space (see Table 3).

**Table 3 The top 10 most used words, and comparison of 40.95 versus Turkish F and Turkish QWERTY keyboards**

|      |           | 40,95               |            | F (optimistic)      |            | QWERTY (optimistic) |            |
|------|-----------|---------------------|------------|---------------------|------------|---------------------|------------|
| Word | Frequency | Distance (diameter) | Time (sec) | Distance (diameter) | Time (sec) | Distance (diameter) | Time (sec) |
| bir  | 48798     | 2                   | 0,41       | 11,19               | 1,1        | 6,83                | 0,87       |
| ve   | 34469     | 1                   | 0,2        | 1,12                | 0,22       | 2,83                | 0,4        |
| bu   | 22905     | 1                   | 0,2        | 7,57                | 0,63       | 2,24                | 0,35       |
| da   | 19647     | 2,65                | 0,38       | 1,8                 | 0,3        | 2                   | 0,32       |
| de   | 19468     | 1                   | 0,2        | 2,69                | 0,38       | 1,12                | 0,22       |
| için | 10927     | 6,29                | 0,97       | 12,87               | 1,46       | 7,89                | 1,14       |
| o    | 8100      | 0                   | 0          | 0                   | 0          | 0                   | 0          |
| çok  | 7899      | 4,61                | 0,65       | 4,93                | 0,73       | 3,35                | 0,57       |
| gibi | 7289      | 4,65                | 0,79       | 14,27               | 1,41       | 8,35                | 1,18       |
| ne   | 7053      | 1                   | 0,2        | 4,61                | 0,51       | 4,47                | 0,5        |

In our proposed keyboard, stylus spends least amount of distance and time compared to the other keyboards. The performance gain of our proposed keyboard comparing distance moved is more than %700. The tables for 2, 3, 4 and 5 character sequences, and more complete version of Table 3, is available at Appendix B. These tables show that our proposed keyboard outperforms current Turkish layouts on very high majority of substrings that user might tap with the stylus.

# Chapter 6

## Conclusion and Future Work

### 6.1 Conclusion

In this study we introduced the first virtual keyboard design for Turkish. We introduced several methodologies, and analyzed Turkish language for obtaining best possible results.

First, we introduced Turkish keyboards that are used today, and we mentioned a bit of history of QWERTY and F Keyboards and discussed even though Turkish F keyboard is better for 10 finger typing, its still offers no advantage to be used as a virtual keyboard.

Second, we introduced our metric: the Fitts' Law and its role in our keyboard design. We tried to keep to the same assumptions as other researchers did. We introduced mean time for typing a character, based on Fitts' Law.

Third, we introduced digraphs and created two digraph tables from METU Corpus, and *ekşi sözlük* corpus. In order to show the similarities between these two digraphs, and the distinction between them and the English corpus digraph, we created digraph coloring and did comparisons between the digraphs. We showed the letter usage frequencies in Turkish corpuses, and stated that there is a letter usage difference between more formal text and less formal text. In this chapter, finally, we discussed the ways to analyze Turkish QWERTY and Turkish F keyboards, and calculated their word per minute performances.

Fourth, we introduced the Fitts'-Digraph Energy function used with both Metropolis Algorithm and KL heuristic. We mentioned that the layout choice of our keyboard will have hexagonal keys as stylus' hits on virtual keys have circular domes, and circles fit into hexagons better. Then, we applied Metropolis Algorithm to our setting and found the best Turkish virtual keyboard. We then extended our study to other possible algorithms, and found that KL heuristic outperforms Metropolis algorithm.

Fifth, we showed that the resulting keyboard has 40.95 wpm which is a %43 to a %50 improvement over the current keyboard layouts. We analyzed KL heuristic's performance by running logs. Finally, we stated that performance of our result is very satisfying.

## 6.2 Future Work

There are several limitations of our work. Firstly, we have not considered any learning curve optimization for possible users of this keyboard. Zhai et al. [19] have added several energy functions to their Metropolis solution in order to ease learning curve. These are alphabetic sorting, and word connectivity enabling users to write very common words in English. These energy functions may be introduced to our keyboard.

Secondly, even though the Fitts' Law has been tested several times, we need to conduct a user test to collect data about the design, and its performance on users. Performance issues such as the angle between the successive keys and other issues such as users' hands' physical capabilities would affect the optimality of this keyboard. Therefore, it is possible to introduce a new metric for stylus input where instead of digraphs consideration we might use digraphs consisting of 3 or more nodes to optimize for any ergonomic performance of human hand with stylus. However this requires a broad research on ergonomics, and results will no longer depend on Fitts' Law.

We did some assumptions as Zhai et al. did in their work [19], for the word per minute calculation. First, every 4 letters plus a space character counts for a word. Second,

the entered text of the users might not fit to the digraph frequency tables' results. Third, the user's text entry performance modeled by Fitts' Law has IP index of 4.9 bps. The Fitts' Law cannot be applied on hexagons, therefore we used the inside fitting circle of the hexagon keys in our calculations. Finally, all per minute calculations of words depend on possible advanced users of this keyboard; we did not consider any time spent searching for letters.

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# Appendix A

## Digraph Tables

Table 1 Digraph of ekSi sözlük

|   |         | a       | b       | c       | ç      | d       | e       | f       | g       | ğ      | h       | ı       | i       | j      | k       | l       | m       |
|---|---------|---------|---------|---------|--------|---------|---------|---------|---------|--------|---------|---------|---------|--------|---------|---------|---------|
|   | 1414018 | 4526513 | 6665949 | 1432988 | 782278 | 4568086 | 2171212 | 1153097 | 3358101 | 301    | 2255110 | 60587   | 3471384 | 139514 | 4462462 | 677491  | 2170012 |
| a | 6399944 | 258086  | 999206  | 833721  | 241986 | 1865890 | 23678   | 454267  | 417238  | 386756 | 998543  | 2438    | 312319  | 73406  | 2920244 | 3303992 | 2355452 |
| b | 40581   | 1706095 | 43149   | 6928    | 95     | 17357   | 1401720 | 1094    | 4190    | 34     | 1550    | 110006  | 4139618 | 9963   | 1140934 | 151361  | 6721    |
| c | 169925  | 1393182 | 17006   | 23708   | 39     | 23479   | 1432075 | 1368    | 4123    | 75     | 292480  | 195285  | 1044193 | 486    | 197346  | 127845  | 57099   |
| ç | 176453  | 317766  | 17293   | 188     | 1494   | 461     | 349738  | 17      | 3376    | 12     | 1133    | 284414  | 462252  | 9      | 8378    | 84817   | 65218   |
| d | 698795  | 4034983 | 10800   | 7416    | 145    | 121762  | 4600286 | 4496    | 11873   | 499    | 5665    | 983693  | 3469079 | 7634   | 7054    | 74789   | 13100   |
| e | 8217889 | 404480  | 386040  | 792923  | 167365 | 1505542 | 296636  | 256647  | 329518  | 334360 | 157266  | 536     | 87875   | 20273  | 2449542 | 2437192 | 1541063 |
| f | 375559  | 570612  | 2533    | 6300    | 2468   | 1669    | 395835  | 68261   | 2373    | 12     | 3313    | 108259  | 548160  | 283    | 9527    | 116980  | 4333    |
| g | 300345  | 462803  | 5407    | 2084    | 66     | 16688   | 1568199 | 1854    | 22780   | 53     | 148752  | 105280  | 1943560 | 185    | 1178    | 143490  | 33677   |
| ğ | 13869   | 82690   | 1327    | 1566    | 224    | 17391   | 109615  | 545     | 118     | 2807   | 249     | 526751  | 620618  | 5      | 503     | 132892  | 33165   |
| h | 372409  | 2059950 | 13935   | 14202   | 15920  | 8367    | 1578298 | 2395    | 1119    | 53     | 32984   | 62156   | 783711  | 818    | 17900   | 67411   | 64585   |
| ı | 1991854 | 1540    | 10147   | 122046  | 24128  | 124651  | 354     | 30629   | 33924   | 360585 | 5178    | 19749   | 338     | 307    | 643258  | 806353  | 570921  |
| i | 6529487 | 143745  | 484184  | 770540  | 459817 | 717364  | 209545  | 275734  | 738668  | 418485 | 185043  | 172     | 153681  | 15246  | 1813793 | 3876581 | 1974531 |
| j | 26943   | 86004   | 791     | 580     | 5      | 8375    | 70542   | 275     | 351     | 6      | 409     | 10478   | 93694   | 1534   | 1981    | 12535   | 1134    |
| k | 3418492 | 2997919 | 16077   | 56940   | 71326  | 27646   | 1540056 | 4646    | 4960    | 263    | 11888   | 642110  | 2300055 | 649    | 149287  | 1339022 | 212137  |
| l | 1352887 | 6420262 | 140654  | 82411   | 20938  | 1131381 | 5332564 | 40560   | 225005  | 332    | 16591   | 1028989 | 3516160 | 3179   | 317894  | 1193864 | 1470792 |
| m | 1831537 | 4048584 | 116079  | 81511   | 647    | 318743  | 2869288 | 5539    | 13010   | 49     | 16902   | 638618  | 2014227 | 898    | 46042   | 540857  | 114563  |
| n | 9135276 | 1830671 | 66411   | 754729  | 65724  | 3513786 | 2441455 | 38504   | 650081  | 106    | 11818   | 1231741 | 3072825 | 10619  | 242401  | 1397299 | 468041  |
| o | 754950  | 37248   | 110899  | 232536  | 7102   | 279888  | 33545   | 261751  | 283820  | 174242 | 81538   | 226     | 58463   | 55352  | 899579  | 2779316 | 464937  |
| ö | 3046    | 346     | 13428   | 4996    | 3516   | 20919   | 1187    | 7139    | 6290    | 65182  | 2893    | 17      | 617     | 102    | 39787   | 137968  | 18691   |
| p | 718125  | 792672  | 1891    | 13810   | 8364   | 5109    | 474093  | 2422    | 5312    | 44     | 62334   | 158435  | 349315  | 646    | 28636   | 346257  | 120732  |
| q | 7319    | 951     | 210     | 93      | 3      | 538     | 256     | 95      | 25      | 1      | 38      | 57      | 450     | 13     | 18      | 1355    | 157     |
| r | 4951989 | 3128909 | 129689  | 241529  | 120330 | 1391224 | 2437030 | 73864   | 205635  | 173    | 64880   | 1218343 | 3691555 | 27080  | 1027556 | 990320  | 801857  |
| s | 1351421 | 2508410 | 14101   | 94290   | 4532   | 11028   | 2078436 | 19515   | 19215   | 41     | 228514  | 1147659 | 3440728 | 996    | 284068  | 429345  | 282860  |
| ş | 465306  | 447650  | 6118    | 2723    | 10699  | 1986    | 354226  | 4043    | 6216    | 28     | 6582    | 370710  | 382220  | 30     | 131159  | 259598  | 177504  |
| t | 1716313 | 2614834 | 46779   | 50859   | 23666  | 9391    | 2346030 | 21093   | 7995    | 215    | 1049813 | 769703  | 2288375 | 693    | 82727   | 533081  | 492810  |
| u | 2073928 | 81498   | 116988  | 275056  | 52931  | 179571  | 87743   | 54704   | 342381  | 250720 | 137058  | 416     | 50901   | 4238   | 566364  | 1256255 | 1006266 |
| ü | 290000  | 809     | 12980   | 54658   | 73376  | 39316   | 8493    | 22408   | 7178    | 78743  | 14322   | 26      | 315     | 1657   | 273933  | 240664  | 320835  |
| v | 56002   | 847062  | 10296   | 26669   | 22     | 60231   | 2022766 | 1155    | 69067   | 15     | 3616    | 17996   | 412915  | 597    | 30353   | 98264   | 28808   |
| w | 119192  | 225802  | 2276    | 1361    | 2      | 2813    | 160173  | 1628    | 668     | 3      | 151462  | 312     | 175812  | 314    | 2036    | 8469    | 1976    |
| x | 47445   | 6328    | 509     | 5083    | 30     | 670     | 10061   | 927     | 184     | 2      | 693     | 142     | 14976   | 41     | 103     | 2750    | 981     |
| y | 775999  | 3469788 | 48560   | 23274   | 596    | 221554  | 1737928 | 25781   | 101659  | 103    | 12117   | 461471  | 898599  | 317    | 58905   | 875464  | 101495  |
| z | 1092135 | 765147  | 13789   | 70225   | 181    | 231834  | 820454  | 259     | 72692   | 40     | 3952    | 260898  | 683116  | 60     | 15416   | 566678  | 148942  |

|   | n       | o       | ö      | p       | q     | r       | s       | ş      | t       | u       | ü      | v       | w      | x     | y       | z       |
|---|---------|---------|--------|---------|-------|---------|---------|--------|---------|---------|--------|---------|--------|-------|---------|---------|
|   | 1034821 | 3623634 | 465427 | 1119695 | 26807 | 702672  | 4691922 | 522190 | 3186184 | 782085  | 276407 | 1885244 | 527112 | 21305 | 3392226 | 542547  |
| a | 7097732 | 19341   | 357    | 930493  | 3994  | 6959955 | 2358725 | 703305 | 2057656 | 95816   | 775    | 513106  | 50755  | 15961 | 2415900 | 1029345 |
| b | 12673   | 520039  | 107531 | 1596    | 71    | 127351  | 16209   | 246    | 4401    | 1600333 | 212531 | 732     | 2377   | 334   | 51849   | 8082    |
| c | 7019    | 517660  | 1371   | 6245    | 8914  | 115395  | 15459   | 17     | 107010  | 455700  | 91429  | 1713    | 462    | 531   | 14807   | 2916    |
| ç | 237     | 255941  | 23563  | 48      | 2     | 2761    | 6122    | 31     | 43770   | 21862   | 68805  | 44      | 2      | 10    | 1199    | 18      |
| d | 18178   | 682212  | 113977 | 3746    | 186   | 135756  | 64195   | 126    | 12965   | 1281673 | 391723 | 11241   | 7368   | 1312  | 75291   | 1148    |
| e | 5269528 | 71853   | 392    | 271048  | 9144  | 6297509 | 1989926 | 245200 | 1808318 | 35847   | 370    | 857098  | 50709  | 60587 | 1340923 | 335579  |
| f | 1618    | 282679  | 5924   | 1260    | 52    | 162780  | 23729   | 542    | 122890  | 112222  | 13064  | 209     | 608    | 802   | 10645   | 463     |
| g | 27515   | 460843  | 423177 | 3341    | 53    | 333347  | 36977   | 28     | 7741    | 661573  | 372521 | 657     | 2308   | 80    | 9321    | 11969   |
| ğ | 4405    | 2327    | 32     | 72      | 1     | 138579  | 2098    | 125    | 205     | 288411  | 76668  | 103     | 8      | 0     | 761     | 11538   |
| h | 62458   | 351664  | 7267   | 9500    | 315   | 89946   | 60547   | 6287   | 277093  | 159454  | 37461  | 21069   | 3520   | 130   | 29608   | 5823    |
| i | 2377022 | 4783    | 84     | 128687  | 141   | 1046610 | 281066  | 550212 | 67683   | 357     | 34     | 17257   | 204    | 69    | 324429  | 428799  |
| ı | 7562586 | 189209  | 232    | 462329  | 6420  | 4879156 | 2425224 | 699539 | 1135090 | 13995   | 470    | 216828  | 1340   | 26644 | 1666874 | 1394350 |
| j | 696     | 51683   | 2620   | 2598    | 12    | 1208    | 898     | 20     | 516     | 56634   | 1286   | 181     | 68     | 71    | 1692    | 79      |
| k | 93461   | 813647  | 94193  | 4769    | 39    | 140689  | 346813  | 23433  | 954721  | 883483  | 182982 | 5392    | 2695   | 258   | 37407   | 1141055 |
| l | 33216   | 460491  | 3355   | 27079   | 394   | 9303    | 236580  | 980    | 281011  | 1153611 | 297887 | 26950   | 9776   | 324   | 165706  | 12461   |
| m | 21549   | 326914  | 2251   | 135402  | 121   | 31162   | 169292  | 6420   | 14471   | 839143  | 283897 | 1981    | 2717   | 1021  | 130445  | 15164   |
| n | 188934  | 419961  | 5606   | 5397    | 2895  | 251467  | 747045  | 8494   | 652389  | 1146609 | 203443 | 17485   | 3224   | 2304  | 211281  | 70954   |
| o | 2121386 | 227003  | 84     | 308063  | 1473  | 2085628 | 406393  | 76263  | 435984  | 642456  | 51     | 150920  | 236324 | 12784 | 528475  | 301258  |
| ö | 292127  | 57      | 9339   | 29933   | 0     | 338749  | 50507   | 10848  | 70560   | 22      | 203    | 16638   | 169    | 23    | 206764  | 324233  |
| p | 5164    | 274223  | 1414   | 48419   | 179   | 265574  | 93707   | 1337   | 190309  | 115991  | 19330  | 803     | 552    | 436   | 20464   | 422     |
| q | 169     | 301     | 0      | 48      | 146   | 339     | 243     | 2      | 322     | 63070   | 12     | 78      | 235    | 35    | 134     | 21      |
| r | 222857  | 644545  | 7406   | 67715   | 2334  | 116854  | 729970  | 114660 | 743759  | 1196679 | 237102 | 92784   | 7635   | 1966  | 210767  | 49788   |
| s | 48894   | 1149928 | 235045 | 167950  | 6745  | 30672   | 267515  | 144    | 1541976 | 868563  | 198670 | 19099   | 28216  | 527   | 154128  | 1718    |
| ş | 2175    | 9701    | 25885  | 1003    | 8     | 7528    | 19958   | 11499  | 385373  | 101546  | 99267  | 10819   | 35     | 7     | 6673    | 600     |
| t | 18020   | 735504  | 30918  | 48384   | 103   | 479789  | 152550  | 258    | 574057  | 858784  | 426917 | 30195   | 26746  | 863   | 75318   | 10412   |
| u | 2450210 | 14746   | 58     | 264676  | 514   | 1868197 | 802333  | 226115 | 545460  | 35240   | 92     | 73036   | 1050   | 10102 | 533349  | 630019  |
| ü | 744261  | 856     | 460    | 58725   | 19    | 533847  | 147932  | 185387 | 89292   | 101     | 6612   | 19286   | 68     | 105   | 152950  | 405404  |
| v | 2378    | 69195   | 255    | 788     | 24    | 135794  | 51028   | 5837   | 1559    | 138169  | 15619  | 22695   | 357    | 1462  | 17667   | 8292    |
| w | 55409   | 106300  | 88     | 630     | 66    | 14420   | 28038   | 108    | 2254    | 2366    | 187    | 1425    | 79873  | 159   | 2492    | 152     |
| x | 285     | 2571    | 4      | 13509   | 69    | 197     | 1123    | 6      | 14513   | 1799    | 35     | 507     | 341    | 6163  | 4084    | 110     |
| y | 254755  | 1578928 | 54607  | 11290   | 51    | 220186  | 130721  | 2880   | 43505   | 507787  | 218039 | 40850   | 9039   | 424   | 27016   | 10355   |
| z | 7559    | 106312  | 1544   | 718     | 103   | 6312    | 38379   | 68     | 6431    | 206671  | 103521 | 1973    | 782    | 212   | 37769   | 42381   |

Table 2 Digraph of METU Corpus

|   |        | a      | b      | c     | ç     | d      | e      | f     | g      | ğ     | h     | ı     | i      | j    | k      | l      |
|---|--------|--------|--------|-------|-------|--------|--------|-------|--------|-------|-------|-------|--------|------|--------|--------|
|   | 170748 | 139508 | 229062 | 15703 | 48280 | 156057 | 66864  | 20558 | 114546 | 10    | 66159 | 5381  | 101947 | 1271 | 157396 | 9467   |
| a | 201630 | 4589   | 28355  | 22267 | 15103 | 55880  | 540    | 10993 | 1482   | 26943 | 26501 | 44    | 6257   | 1678 | 99851  | 99618  |
| b | 1401   | 67571  | 525    | 68    | 5     | 2962   | 38234  | 28    | 9      | 0     | 20    | 4389  | 113435 | 92   | 67     | 1475   |
| c | 461    | 35847  | 137    | 202   | 0     | 378    | 37151  | 6     | 8      | 0     | 1998  | 11389 | 14561  | 0    | 370    | 1123   |
| ç | 11066  | 17185  | 1843   | 11    | 60    | 8      | 20586  | 0     | 82     | 0     | 67    | 18870 | 30065  | 0    | 583    | 6398   |
| d | 2424   | 134992 | 219    | 24    | 3     | 4369   | 158024 | 15    | 179    | 4     | 156   | 60357 | 95582  | 73   | 293    | 1237   |
| e | 227698 | 1097   | 7136   | 23427 | 12595 | 48397  | 739    | 6802  | 1531   | 23175 | 3952  | 30    | 542    | 663  | 74790  | 80092  |
| f | 4529   | 14291  | 44     | 10    | 165   | 14     | 7311   | 598   | 90     | 0     | 45    | 4536  | 7957   | 0    | 508    | 3022   |
| g | 978    | 9312   | 14     | 13    | 0     | 93     | 51883  | 5     | 67     | 0     | 282   | 3829  | 32532  | 11   | 108    | 402    |
| ğ | 819    | 8222   | 206    | 126   | 16    | 1193   | 5832   | 17    | 5      | 1     | 3     | 37973 | 39563  | 1    | 8      | 9047   |
| h | 4398   | 51361  | 566    | 48    | 1078  | 424    | 19298  | 36    | 6      | 0     | 252   | 2389  | 15588  | 2    | 1623   | 3093   |
| ı | 120422 | 97     | 1321   | 3998  | 949   | 4890   | 21     | 1576  | 60     | 24963 | 215   | 331   | 27     | 5    | 40707  | 49632  |
| i | 175972 | 2395   | 11484  | 5390  | 27391 | 14825  | 755    | 5874  | 1991   | 22966 | 8008  | 27    | 2407   | 205  | 46283  | 110715 |
| j | 460    | 881    | 1      | 14    | 0     | 172    | 1237   | 0     | 1      | 0     | 0     | 546   | 2386   | 3    | 8      | 314    |
| k | 105932 | 108626 | 689    | 139   | 3703  | 775    | 45442  | 268   | 221    | 305   | 320   | 29658 | 66288  | 3    | 4863   | 50367  |
| l | 37500  | 214462 | 1540   | 1786  | 2139  | 40176  | 183773 | 354   | 9255   | 24    | 695   | 61084 | 95213  | 35   | 12623  | 24508  |
| m | 45879  | 115907 | 2060   | 2901  | 27    | 10245  | 81149  | 508   | 493    | 1     | 1900  | 31059 | 54146  | 1    | 1365   | 18670  |
| n | 282299 | 59773  | 2805   | 23661 | 4127  | 107325 | 73163  | 901   | 7607   | 0     | 481   | 76309 | 81450  | 152  | 9915   | 51845  |
| o | 10945  | 228    | 1823   | 5588  | 526   | 4039   | 202    | 1836  | 1705   | 14323 | 601   | 10    | 306    | 1964 | 25013  | 71204  |
| ö | 163    | 0      | 603    | 201   | 329   | 1821   | 0      | 350   | 85     | 4325  | 88    | 0     | 18     | 0    | 2501   | 7094   |
| p | 19876  | 22670  | 6      | 47    | 301   | 58     | 8830   | 8     | 51     | 0     | 725   | 10149 | 5435   | 0    | 1381   | 11024  |
| q | 19     | 4      | 0      | 0     | 0     | 0      | 0      | 0     | 0      | 0     | 0     | 1     | 7      | 0    | 1      | 0      |
| r | 131327 | 105163 | 4934   | 3701  | 6264  | 57673  | 67081  | 1080  | 8456   | 1     | 1887  | 77925 | 99540  | 602  | 32043  | 40036  |
| s | 9095   | 67102  | 367    | 575   | 118   | 115    | 46133  | 438   | 246    | 1     | 1041  | 60536 | 67235  | 0    | 7667   | 9181   |
| ş | 21529  | 22497  | 2159   | 48    | 889   | 180    | 14785  | 158   | 436    | 0     | 234   | 25411 | 20140  | 0    | 13234  | 18004  |
| t | 32269  | 74461  | 1407   | 311   | 2252  | 341    | 64500  | 901   | 152    | 2     | 1394  | 50652 | 63294  | 2    | 4034   | 18862  |
| u | 62327  | 1673   | 2349   | 2822  | 4234  | 3808   | 428    | 1077  | 2154   | 15869 | 2692  | 9     | 287    | 33   | 14636  | 38164  |
| ü | 17182  | 49     | 550    | 2707  | 5431  | 2894   | 205    | 924   | 33     | 4216  | 376   | 7     | 5      | 79   | 17316  | 17397  |
| v | 1713   | 25165  | 139    | 1097  | 2     | 1817   | 59001  | 39    | 1509   | 0     | 121   | 627   | 10695  | 2    | 512    | 5875   |
| w | 270    | 404    | 5      | 1     | 0     | 8      | 264    | 4     | 6      | 0     | 45    | 1     | 223    | 0    | 1      | 14     |
| x | 155    | 40     | 1      | 17    | 1     | 0      | 11     | 13    | 0      | 0     | 5     | 34    | 63     | 0    | 0      | 6      |
| y | 9555   | 124303 | 1398   | 356   | 42    | 11759  | 63338  | 710   | 4505   | 0     | 618   | 29505 | 18950  | 0    | 2353   | 34518  |
| z | 32672  | 23103  | 344    | 2132  | 66    | 10133  | 25119  | 1     | 3129   | 1     | 156   | 13063 | 14537  | 0    | 890    | 16320  |

|   | m     | n      | o     | ö     | p     | q  | r      | s      | ş     | t     | u     | ü     | v     | w   | x   | y      | z     |
|---|-------|--------|-------|-------|-------|----|--------|--------|-------|-------|-------|-------|-------|-----|-----|--------|-------|
|   | 58243 | 25672  | 89445 | 34677 | 29825 | 39 | 16167  | 125706 | 24339 | 80355 | 20113 | 19548 | 62070 | 720 | 84  | 127918 | 14538 |
| a | 64844 | 207194 | 270   | 33    | 28858 | 27 | 234181 | 62324  | 52479 | 52608 | 650   | 16    | 17003 | 72  | 63  | 74877  | 32204 |
| b | 1028  | 117    | 10033 | 5996  | 28    | 0  | 2727   | 53     | 5     | 18    | 49910 | 10857 | 12    | 5   | 0   | 96     | 256   |
| c | 230   | 79     | 1342  | 41    | 10    | 58 | 907    | 49     | 0     | 150   | 10231 | 3139  | 6     | 1   | 0   | 47     | 170   |
| ç | 3259  | 2      | 13547 | 1973  | 5     | 0  | 185    | 316    | 0     | 3146  | 1651  | 4734  | 1     | 0   | 0   | 39     | 0     |
| d | 52    | 137    | 17963 | 7514  | 156   | 0  | 2083   | 417    | 0     | 116   | 41583 | 26325 | 123   | 31  | 0   | 1177   | 12    |
| e | 49883 | 149608 | 1312  | 9     | 6947  | 5  | 193705 | 47680  | 14656 | 63280 | 582   | 15    | 25050 | 332 | 150 | 40046  | 12251 |
| f | 28    | 20     | 4442  | 411   | 17    | 0  | 1897   | 261    | 13    | 3020  | 1422  | 352   | 2     | 2   | 1   | 283    | 9     |
| g | 269   | 108    | 1318  | 27396 | 27    | 0  | 3876   | 154    | 0     | 232   | 5619  | 23102 | 39    | 5   | 1   | 34     | 61    |
| ğ | 1501  | 212    | 106   | 2     | 0     | 0  | 9035   | 143    | 6     | 4     | 18092 | 4200  | 2     | 0   | 0   | 3      | 533   |
| h | 2328  | 919    | 2828  | 88    | 1018  | 2  | 1913   | 1313   | 283   | 2654  | 4250  | 3541  | 922   | 18  | 0   | 309    | 184   |
| ı | 32934 | 147371 | 231   | 2     | 6438  | 3  | 46115  | 13171  | 33051 | 4806  | 53    | 2     | 811   | 0   | 18  | 26229  | 20286 |
| i | 51488 | 185471 | 844   | 70    | 8985  | 27 | 124649 | 42376  | 38927 | 23194 | 105   | 9     | 3399  | 9   | 71  | 64350  | 35312 |
| j | 105   | 5      | 301   | 60    | 4     | 0  | 7      | 7      | 0     | 3     | 279   | 32    | 5     | 1   | 0   | 21     | 1     |
| k | 6072  | 1828   | 29448 | 5399  | 1581  | 0  | 6538   | 9934   | 1329  | 29344 | 26309 | 12638 | 253   | 5   | 0   | 1180   | 70    |
| l | 38554 | 1864   | 6167  | 107   | 557   | 0  | 49     | 4245   | 103   | 9869  | 34769 | 14214 | 488   | 2   | 0   | 6104   | 326   |
| m | 1687  | 703    | 4470  | 201   | 1793  | 0  | 864    | 6321   | 484   | 267   | 20616 | 13693 | 99    | 11  | 0   | 533    | 774   |
| n | 15420 | 3228   | 5757  | 254   | 98    | 1  | 7735   | 13341  | 498   | 12397 | 40379 | 13720 | 319   | 10  | 1   | 5440   | 1839  |
| o | 7373  | 53551  | 512   | 0     | 9665  | 4  | 74731  | 6427   | 4072  | 6898  | 500   | 0     | 1361  | 312 | 43  | 9551   | 2337  |
| ö | 1205  | 23737  | 0     | 93    | 1212  | 0  | 21708  | 2933   | 838   | 2950  | 0     | 0     | 1214  | 1   | 0   | 14679  | 17219 |
| p | 2660  | 59     | 6085  | 22    | 173   | 0  | 6356   | 2217   | 8     | 5399  | 1759  | 695   | 5     | 0   | 0   | 242    | 4     |
| q | 0     | 0      | 0     | 0     | 0     | 0  | 0      | 1      | 0     | 0     | 183   | 1     | 0     | 0   | 0   | 0      | 0     |
| r | 24304 | 3715   | 10557 | 705   | 1856  | 18 | 1185   | 14624  | 7119  | 27028 | 37787 | 16252 | 1653  | 22  | 88  | 1341   | 1001  |
| s | 3659  | 630    | 26668 | 10637 | 2201  | 29 | 918    | 3044   | 0     | 32293 | 20205 | 10649 | 268   | 34  | 2   | 5019   | 16    |
| ş | 14311 | 140    | 443   | 1663  | 79    | 0  | 404    | 1119   | 52    | 26827 | 6664  | 6892  | 1178  | 0   | 0   | 445    | 9     |
| t | 12981 | 415    | 14303 | 1771  | 218   | 0  | 7479   | 2300   | 0     | 16406 | 20768 | 27772 | 1455  | 44  | 6   | 354    | 160   |
| u | 27823 | 62557  | 387   | 0     | 5105  | 16 | 41812  | 12474  | 14662 | 11215 | 176   | 0     | 2218  | 10  | 62  | 19250  | 14866 |
| ü | 14101 | 46410  | 25    | 5     | 1790  | 0  | 36048  | 7909   | 14212 | 6165  | 1     | 20    | 1885  | 0   | 0   | 13204  | 22312 |
| v | 450   | 60     | 608   | 4     | 0     | 0  | 6337   | 468    | 283   | 17    | 5143  | 625   | 659   | 2   | 0   | 209    | 213   |
| w | 0     | 44     | 182   | 2     | 5     | 0  | 28     | 65     | 0     | 19    | 8     | 0     | 0     | 59  | 0   | 11     | 0     |
| x | 1     | 1      | 18    | 0     | 16    | 0  | 0      | 1      | 0     | 33    | 5     | 0     | 8     | 3   | 20  | 11     | 0     |
| y | 2357  | 5777   | 64407 | 5084  | 538   | 0  | 5430   | 3326   | 257   | 640   | 11043 | 18424 | 603   | 27  | 0   | 872    | 308   |
| z | 4571  | 314    | 3200  | 50    | 37    | 0  | 158    | 925    | 1     | 158   | 4350  | 5726  | 74    | 5   | 0   | 1559   | 494   |

Table 3 Digraph of Sourkernoff, &amp; Mackenzie

|   | a    | b    | c   | d    | e    | f    | g   | h    | i   | j  | k   | l   | m   | n    | o   | p   | q  | r    | s    | t    | u    | v   | w    | x  | y   | z  |      |
|---|------|------|-----|------|------|------|-----|------|-----|----|-----|-----|-----|------|-----|-----|----|------|------|------|------|-----|------|----|-----|----|------|
| a | 2    | 144  | 308 | 382  | 1    | 67   | 138 | 9    | 322 | 7  | 146 | 664 | 177 | 1576 | 1   | 100 | 0  | 802  | 683  | 785  | 87   | 233 | 57   | 14 | 319 | 12 | 50   |
| b | 136  | 14   | 0   | 0    | 415  | 0    | 0   | 0    | 78  | 18 | 0   | 98  | 1   | 0    | 240 | 0   | 0  | 88   | 15   | 7    | 256  | 1   | 1    | 0  | 13  | 0  | 36   |
| c | 368  | 0    | 13  | 0    | 285  | 0    | 0   | 412  | 67  | 0  | 178 | 108 | 0   | 1    | 298 | 0   | 1  | 71   | 7    | 154  | 34   | 0   | 0    | 0  | 9   | 0  | 47   |
| d | 106  | 1    | 0   | 37   | 375  | 3    | 19  | 0    | 148 | 1  | 0   | 22  | 1   | 2    | 137 | 0   | 0  | 83   | 95   | 3    | 52   | 5   | 2    | 0  | 51  | 0  | 2627 |
| e | 670  | 8    | 181 | 767  | 470  | 103  | 46  | 15   | 127 | 1  | 35  | 332 | 187 | 799  | 44  | 90  | 9  | 1314 | 630  | 316  | 8    | 172 | 106  | 87 | 189 | 2  | 4904 |
| f | 145  | 0    | 0   | 0    | 154  | 86   | 0   | 0    | 205 | 0  | 0   | 69  | 3   | 0    | 429 | 0   | 0  | 188  | 4    | 102  | 62   | 0   | 0    | 0  | 4   | 0  | 110  |
| g | 94   | 1    | 0   | 0    | 289  | 0    | 19  | 288  | 96  | 0  | 0   | 55  | 1   | 31   | 135 | 0   | 0  | 98   | 42   | 6    | 57   | 0   | 1    | 0  | 2   | 0  | 686  |
| h | 1164 | 0    | 0   | 0    | 3155 | 0    | 0   | 1    | 824 | 0  | 0   | 5   | 1   | 0    | 487 | 2   | 0  | 91   | 8    | 165  | 75   | 0   | 8    | 0  | 32  | 0  | 715  |
| i | 23   | 7    | 304 | 260  | 189  | 56   | 233 | 0    | 1   | 0  | 86  | 324 | 255 | 1110 | 88  | 42  | 2  | 272  | 484  | 558  | 5    | 165 | 0    | 15 | 0   | 18 | 4    |
| j | 2    | 0    | 0   | 0    | 31   | 0    | 0   | 0    | 9   | 0  | 0   | 0   | 0   | 0    | 41  | 0   | 0  | 0    | 0    | 0    | 56   | 0   | 0    | 0  | 0   | 0  | 0    |
| k | 2    | 0    | 0   | 0    | 337  | 0    | 0   | 0    | 127 | 0  | 0   | 10  | 1   | 82   | 3   | 1   | 0  | 0    | 50   | 0    | 3    | 0   | 0    | 0  | 8   | 0  | 309  |
| l | 332  | 4    | 6   | 289  | 591  | 59   | 7   | 0    | 390 | 0  | 38  | 546 | 30  | 1    | 344 | 34  | 0  | 11   | 121  | 74   | 81   | 17  | 19   | 0  | 276 | 0  | 630  |
| m | 394  | 50   | 0   | 0    | 530  | 6    | 0   | 0    | 165 | 0  | 0   | 4   | 28  | 4    | 289 | 77  | 0  | 0    | 53   | 2    | 85   | 0   | 0    | 0  | 19  | 0  | 454  |
| n | 100  | 2    | 98  | 1213 | 512  | 5    | 771 | 5    | 135 | 8  | 63  | 80  | 0   | 54   | 349 | 0   | 3  | 2    | 148  | 378  | 49   | 3   | 2    | 2  | 115 | 0  | 1152 |
| o | 65   | 67   | 61  | 119  | 34   | 80   | 9   | 1    | 88  | 3  | 123 | 218 | 417 | 598  | 336 | 138 | 0  | 812  | 195  | 415  | 1115 | 136 | 398  | 2  | 47  | 5  | 294  |
| p | 142  | 0    | 1   | 0    | 280  | 1    | 0   | 24   | 97  | 0  | 0   | 169 | 0   | 0    | 149 | 64  | 0  | 110  | 48   | 40   | 68   | 0   | 3    | 0  | 14  | 0  | 127  |
| q | 0    | 0    | 0   | 0    | 0    | 0    | 0   | 0    | 0   | 0  | 0   | 0   | 0   | 0    | 0   | 0   | 0  | 0    | 0    | 0    | 66   | 0   | 0    | 0  | 0   | 0  | 0    |
| r | 289  | 10   | 22  | 133  | 1139 | 13   | 59  | 21   | 309 | 0  | 53  | 71  | 65  | 106  | 504 | 9   | 0  | 69   | 318  | 190  | 89   | 22  | 5    | 0  | 145 | 0  | 1483 |
| s | 196  | 9    | 47  | 0    | 626  | 0    | 1   | 328  | 214 | 0  | 57  | 48  | 31  | 16   | 213 | 107 | 8  | 0    | 168  | 754  | 175  | 0   | 32   | 0  | 34  | 0  | 2228 |
| t | 259  | 2    | 31  | 1    | 583  | 1    | 2   | 3774 | 252 | 0  | 0   | 75  | 1   | 2    | 331 | 0   | 0  | 187  | 209  | 154  | 132  | 0   | 84   | 0  | 121 | 1  | 2343 |
| u | 45   | 53   | 114 | 48   | 71   | 10   | 148 | 0    | 65  | 0  | 0   | 247 | 87  | 278  | 3   | 49  | 1  | 402  | 299  | 492  | 0    | 0   | 0    | 1  | 7   | 3  | 255  |
| v | 27   | 0    | 0   | 0    | 683  | 0    | 0   | 0    | 109 | 0  | 0   | 0   | 0   | 0    | 33  | 0   | 0  | 0    | 0    | 0    | 1    | 0   | 0    | 0  | 11  | 0  | 0    |
| w | 595  | 3    | 0   | 6    | 285  | 0    | 0   | 472  | 374 | 0  | 1   | 12  | 0   | 103  | 264 | 0   | 0  | 35   | 21   | 4    | 2    | 0   | 0    | 0  | 0   | 0  | 326  |
| x | 17   | 0    | 9   | 0    | 9    | 0    | 0   | 0    | 10  | 0  | 0   | 0   | 0   | 0    | 1   | 22  | 0  | 0    | 0    | 0    | 23   | 8   | 0    | 0  | 0   | 0  | 21   |
| y | 11   | 10   | 0   | 0    | 152  | 0    | 1   | 1    | 32  | 0  | 0   | 7   | 1   | 0    | 339 | 16  | 0  | 0    | 81   | 2    | 1    | 0   | 2    | 0  | 0   | 0  | 1171 |
| z | 3    | 0    | 0   | 0    | 26   | 0    | 0   | 0    | 2   | 0  | 0   | 4   | 0   | 0    | 2   | 0   | 0  | 0    | 3    | 0    | 0    | 0   | 0    | 0  | 3   | 9  | 2    |
|   | 1882 | 1033 | 864 | 515  | 423  | 1059 | 453 | 1388 | 237 | 93 | 152 | 717 | 876 | 478  | 721 | 588 | 42 | 494  | 1596 | 3912 | 134  | 116 | 1787 | 0  | 436 | 2  | 0    |

Table 4 Digraph of Zhai, Hunter, &amp; Smith's Chat Corpus

|   | a     | b     | c    | d    | e    | f     | g    | h    | i     | j     | k    | l    | m    | n    | o     | p     | q    | r   | s     | t     | u     | v     | w    | x     | y    | z    |     |
|---|-------|-------|------|------|------|-------|------|------|-------|-------|------|------|------|------|-------|-------|------|-----|-------|-------|-------|-------|------|-------|------|------|-----|
|   | 4009  | 21745 | 9578 | 9261 | 7650 | 3973  | 6532 | 6755 | 10090 | 17781 | 2193 | 2323 | 5576 | 9862 | 5798  | 10647 | 6528 | 473 | 4274  | 12637 | 28897 | 2468  | 1107 | 14233 | 116  | 6056 | 75  |
| a | 7498  | 465   | 1809 | 2574 | 2828 | 95    | 402  | 1543 | 1653  | 2545  | 100  | 1584 | 7926 | 2721 | 17032 | 71    | 1150 | 7   | 8083  | 6395  | 12701 | 1425  | 2409 | 539   | 87   | 2854 | 399 |
| b | 245   | 1810  | 290  | 34   | 115  | 5033  | 8    | 9    | 10    | 1338  | 145  | 4    | 1831 | 7    | 30    | 2337  | 6    | 0   | 895   | 257   | 99    | 1994  | 71   | 24    | 0    | 696  | 10  |
| c | 777   | 4074  | 15   | 446  | 46   | 3020  | 2    | 9    | 5429  | 1316  | 3    | 2494 | 829  | 8    | 12    | 3576  | 13   | 6   | 1083  | 481   | 1771  | 688   | 3    | 0     | 0    | 186  | 26  |
| d | 14705 | 1610  | 34   | 108  | 305  | 4356  | 48   | 213  | 51    | 2814  | 14   | 3    | 228  | 130  | 520   | 4263  | 6    | 5   | 749   | 1038  | 27    | 758   | 50   | 27    | 1    | 582  | 15  |
| e | 34370 | 6619  | 426  | 2027 | 5349 | 3716  | 990  | 620  | 1038  | 1683  | 49   | 342  | 5488 | 2220 | 7563  | 1049  | 958  | 96  | 13449 | 8729  | 3606  | 181   | 2544 | 1036  | 1313 | 2232 | 106 |
| f | 5784  | 1597  | 0    | 6    | 20   | 1523  | 1122 | 89   | 2     | 1546  | 3    | 15   | 405  | 15   | 9     | 2872  | 1    | 0   | 1444  | 64    | 375   | 1046  | 0    | 2     | 9    | 70   | 0   |
| g | 5761  | 1275  | 12   | 5    | 60   | 2665  | 13   | 294  | 1875  | 2153  | 4    | 4    | 546  | 59   | 292   | 3949  | 0    | 1   | 1184  | 567   | 43    | 1108  | 4    | 8     | 0    | 181  | 1   |
| h | 4624  | 12788 | 52   | 33   | 37   | 21947 | 22   | 9    | 414   | 7138  | 6    | 26   | 57   | 234  | 342   | 4669  | 12   | 3   | 1041  | 117   | 1359  | 1137  | 13   | 48    | 8    | 775  | 0   |
| i | 6295  | 1759  | 687  | 4239 | 2615 | 3136  | 2381 | 2018 | 35    | 410   | 16   | 1141 | 3110 | 2719 | 16266 | 3034  | 633  | 93  | 2734  | 9766  | 9615  | 86    | 1543 | 27    | 106  | 42   | 203 |
| j | 51    | 486   | 3    | 11   | 2    | 1098  | 0    | 5    | 7     | 38    | 16   | 8    | 0    | 0    | 5     | 596   | 3    | 0   | 18    | 9     | 11    | 1072  | 169  | 18    | 0    | 0    | 0   |
| k | 2491  | 701   | 17   | 6    | 11   | 3063  | 15   | 14   | 381   | 2009  | 169  | 21   | 86   | 13   | 1171  | 300   | 10   | 0   | 80    | 944   | 63    | 72    | 5    | 50    | 0    | 203  | 0   |
| l | 5774  | 3227  | 230  | 165  | 2253 | 6082  | 542  | 144  | 17    | 5395  | 1    | 543  | 7169 | 143  | 27    | 4721  | 214  | 0   | 150   | 1510  | 429   | 716   | 182  | 175   | 6    | 3350 | 92  |
| m | 4209  | 4265  | 412  | 74   | 60   | 7113  | 28   | 13   | 16    | 1812  | 1    | 10   | 61   | 1022 | 219   | 2506  | 876  | 0   | 31    | 1145  | 54    | 1037  | 0    | 8     | 1    | 1208 | 1   |
| n | 12907 | 3056  | 77   | 1760 | 7938 | 5569  | 265  | 7641 | 43    | 2349  | 97   | 1359 | 616  | 75   | 1453  | 6352  | 51   | 19  | 108   | 2630  | 5478  | 448   | 180  | 37    | 28   | 2539 | 21  |
| o | 10884 | 282   | 794  | 1164 | 3161 | 863   | 4755 | 630  | 983   | 974   | 95   | 1122 | 3200 | 4208 | 11489 | 4163  | 1896 | 6   | 8040  | 2002  | 4866  | 11567 | 1130 | 3698  | 115  | 327  | 80  |
| p | 1205  | 1441  | 12   | 20   | 6    | 3161  | 12   | 8    | 708   | 1724  | 2    | 13   | 2029 | 46   | 2     | 1902  | 935  | 0   | 1911  | 567   | 598   | 581   | 1    | 0     | 1    | 153  | 0   |
| q | 10    | 8     | 2    | 0    | 0    | 1     | 0    | 0    | 0     | 0     | 0    | 0    | 1    | 1    | 1     | 1     | 0    | 0   | 0     | 1     | 0     | 768   | 1    | 2     | 0    | 0    | 0   |
| r | 8898  | 3884  | 310  | 750  | 1500 | 13277 | 210  | 727  | 100   | 4628  | 11   | 646  | 1229 | 511  | 909   | 4490  | 234  | 1   | 901   | 2702  | 1991  | 1387  | 267  | 133   | 10   | 1974 | 9   |
| s | 22762 | 3168  | 111  | 934  | 57   | 6075  | 58   | 647  | 2816  | 2744  | 11   | 364  | 595  | 634  | 616   | 3901  | 1177 | 30  | 52    | 2298  | 8368  | 2183  | 17   | 312   | 5    | 356  | 10  |
| t | 23464 | 3453  | 60   | 457  | 45   | 6273  | 48   | 61   | 25793 | 6133  | 13   | 12   | 677  | 107  | 92    | 8430  | 87   | 2   | 2334  | 2391  | 1605  | 1493  | 49   | 326   | 7    | 1268 | 38  |
| u | 4320  | 686   | 391  | 1247 | 713  | 1016  | 411  | 1001 | 174   | 591   | 19   | 197  | 2667 | 946  | 2631  | 137   | 1182 | 2   | 3885  | 5087  | 4058  | 98    | 11   | 10    | 32   | 492  | 69  |
| v | 310   | 474   | 6    | 7    | 2    | 7300  | 1    | 5    | 5     | 1583  | 0    | 0    | 8    | 3    | 9     | 489   | 0    | 0   | 7     | 16    | 8     | 7     | 2    | 0     | 0    | 10   | 0   |
| w | 2298  | 4759  | 94   | 3    | 21   | 3235  | 18   | 7    | 4332  | 3350  | 5    | 9    | 138  | 7    | 570   | 2410  | 5    | 0   | 382   | 365   | 34    | 73    | 1    | 242   | 0    | 19   | 1   |
| x | 251   | 234   | 0    | 114  | 6    | 125   | 1    | 2    | 5     | 330   | 0    | 1    | 6    | 0    | 0     | 17    | 250  | 0   | 2     | 7     | 197   | 42    | 0    | 3     | 88   | 91   | 0   |
| y | 11413 | 514   | 272  | 68   | 25   | 1784  | 101  | 118  | 35    | 406   | 1    | 82   | 66   | 147  | 61    | 6542  | 127  | 1   | 82    | 935   | 401   | 182   | 2    | 130   | 1    | 131  | 19  |
| z | 191   | 94    | 0    | 0    | 3    | 227   | 0    | 1    | 2     | 124   | 0    | 34   | 6    | 2    | 5     | 55    | 0    | 0   | 1     | 2     | 3     | 27    | 0    | 1     | 0    | 96   | 132 |

Table 5 Table 4 Digraph of Zhai, Hunter, &amp; Smith's News Corpus

|   | a     | b     | c    | d    | e    | f     | g    | h    | i     | j     | k    | l    | m    | n    | o     | p     | q    | r   | s     | t     | u     | v     | w    | x     | y    | z    |     |
|---|-------|-------|------|------|------|-------|------|------|-------|-------|------|------|------|------|-------|-------|------|-----|-------|-------|-------|-------|------|-------|------|------|-----|
|   | 4009  | 21745 | 9578 | 9261 | 7650 | 3973  | 6532 | 6755 | 10090 | 17781 | 2193 | 2323 | 5576 | 9862 | 5798  | 10647 | 6528 | 473 | 4274  | 12637 | 28897 | 2468  | 1107 | 14233 | 116  | 6056 | 75  |
| a | 7498  | 465   | 1809 | 2574 | 2828 | 95    | 402  | 1543 | 1653  | 2545  | 100  | 1584 | 7926 | 2721 | 17032 | 71    | 1150 | 7   | 8083  | 6395  | 12701 | 1425  | 2409 | 539   | 87   | 2854 | 399 |
| b | 245   | 1810  | 290  | 34   | 115  | 5033  | 8    | 9    | 10    | 1338  | 145  | 4    | 1831 | 7    | 30    | 2337  | 6    | 0   | 895   | 257   | 99    | 1994  | 71   | 24    | 0    | 696  | 10  |
| c | 777   | 4074  | 15   | 446  | 46   | 3020  | 2    | 9    | 5429  | 1316  | 3    | 2494 | 829  | 8    | 12    | 3576  | 13   | 6   | 1083  | 481   | 1771  | 688   | 3    | 0     | 0    | 186  | 26  |
| d | 14705 | 1610  | 34   | 108  | 305  | 4356  | 48   | 213  | 51    | 2814  | 14   | 3    | 228  | 130  | 520   | 4263  | 6    | 5   | 749   | 1038  | 27    | 758   | 50   | 27    | 1    | 582  | 15  |
| e | 34370 | 6619  | 426  | 2027 | 5349 | 3716  | 990  | 620  | 1038  | 1683  | 49   | 342  | 5488 | 2220 | 7563  | 1049  | 958  | 96  | 13449 | 8729  | 3606  | 181   | 2544 | 1036  | 1313 | 2232 | 106 |
| f | 5784  | 1597  | 0    | 6    | 20   | 1523  | 1122 | 89   | 2     | 1546  | 3    | 15   | 405  | 15   | 9     | 2872  | 1    | 0   | 1444  | 64    | 375   | 1046  | 0    | 2     | 9    | 70   | 0   |
| g | 5761  | 1275  | 12   | 5    | 60   | 2665  | 13   | 294  | 1875  | 2153  | 4    | 4    | 546  | 59   | 292   | 3949  | 0    | 1   | 1184  | 567   | 43    | 1108  | 4    | 8     | 0    | 181  | 1   |
| h | 4624  | 12788 | 52   | 33   | 37   | 21947 | 22   | 9    | 414   | 7138  | 6    | 26   | 57   | 234  | 342   | 4669  | 12   | 3   | 1041  | 117   | 1359  | 1137  | 13   | 48    | 8    | 775  | 0   |
| i | 6295  | 1759  | 687  | 4239 | 2615 | 3136  | 2381 | 2018 | 35    | 410   | 16   | 1141 | 3110 | 2719 | 16266 | 3034  | 633  | 93  | 2734  | 9766  | 9615  | 86    | 1543 | 27    | 106  | 42   | 203 |
| j | 51    | 486   | 3    | 11   | 2    | 1098  | 0    | 5    | 7     | 38    | 16   | 8    | 0    | 0    | 5     | 596   | 3    | 0   | 18    | 9     | 11    | 1072  | 169  | 18    | 0    | 0    | 0   |
| k | 2491  | 701   | 17   | 6    | 11   | 3063  | 15   | 14   | 381   | 2009  | 169  | 21   | 86   | 13   | 1171  | 300   | 10   | 0   | 80    | 944   | 63    | 72    | 5    | 50    | 0    | 203  | 0   |
| l | 5774  | 3227  | 230  | 165  | 2253 | 6082  | 542  | 144  | 17    | 5395  | 1    | 543  | 7169 | 143  | 27    | 4721  | 214  | 0   | 150   | 1510  | 429   | 716   | 182  | 175   | 6    | 3350 | 92  |
| m | 4209  | 4265  | 412  | 74   | 60   | 7113  | 28   | 13   | 16    | 1812  | 1    | 10   | 61   | 1022 | 219   | 2506  | 876  | 0   | 31    | 1145  | 54    | 1037  | 0    | 8     | 1    | 1208 | 1   |
| n | 12907 | 3056  | 77   | 1760 | 7938 | 5569  | 265  | 7641 | 43    | 2349  | 97   | 1359 | 616  | 75   | 1453  | 6352  | 51   | 19  | 108   | 2630  | 5478  | 448   | 180  | 37    | 28   | 2539 | 21  |
| o | 10884 | 282   | 794  | 1164 | 3161 | 863   | 4755 | 630  | 983   | 974   | 95   | 1122 | 3200 | 4208 | 11489 | 4163  | 1896 | 6   | 8040  | 2002  | 4866  | 11567 | 1130 | 3698  | 115  | 327  | 80  |
| p | 1205  | 1441  | 12   | 20   | 6    | 3161  | 12   | 8    | 708   | 1724  | 2    | 13   | 2029 | 46   | 2     | 1902  | 935  | 0   | 1911  | 567   | 598   | 581   | 1    | 0     | 1    | 153  | 0   |
| q | 10    | 8     | 2    | 0    | 0    | 1     | 0    | 0    | 0     | 0     | 0    | 0    | 1    | 1    | 1     | 1     | 0    | 0   | 0     | 1     | 0     | 768   | 1    | 2     | 0    | 0    | 0   |
| r | 8898  | 3884  | 310  | 750  | 1500 | 13277 | 210  | 727  | 100   | 4628  | 11   | 646  | 1229 | 511  | 909   | 4490  | 234  | 1   | 901   | 2702  | 1991  | 1387  | 267  | 133   | 10   | 1974 | 9   |
| s | 22762 | 3168  | 111  | 934  | 57   | 6075  | 58   | 647  | 2816  | 2744  | 11   | 364  | 595  | 634  | 616   | 3901  | 1177 | 30  | 52    | 2298  | 8368  | 2183  | 17   | 312   | 5    | 356  | 10  |
| t | 23464 | 3453  | 60   | 457  | 45   | 6273  | 48   | 61   | 25793 | 6133  | 13   | 12   | 677  | 107  | 92    | 8430  | 87   | 2   | 2334  | 2391  | 1605  | 1493  | 49   | 326   | 7    | 1268 | 38  |
| u | 4320  | 686   | 391  | 1247 | 713  | 1016  | 411  | 1001 | 174   | 591   | 19   | 197  | 2667 | 946  | 2631  | 137   | 1182 | 2   | 3885  | 5087  | 4058  | 98    | 11   | 10    | 32   | 492  | 69  |
| v | 310   | 474   | 6    | 7    | 2    | 7300  | 1    | 5    | 5     | 1583  | 0    | 0    | 8    | 3    | 9     | 489   | 0    | 0   | 7     | 16    | 8     | 7     | 2    | 0     | 0    | 10   | 0   |
| w | 2298  | 4759  | 94   | 3    | 21   | 3235  | 18   | 7    | 4332  | 3350  | 5    | 9    | 138  | 7    | 570   | 2410  | 5    | 0   | 382   | 365   | 34    | 73    | 1    | 242   | 0    | 19   | 1   |
| x | 251   | 234   | 0    | 114  | 6    | 125   | 1    | 2    | 5     | 330   | 0    | 1    | 6    | 0    | 0     | 17    | 250  | 0   | 2     | 7     | 197   | 42    | 0    | 3     | 88   | 91   | 0   |
| y | 11413 | 514   | 272  | 68   | 25   | 1784  | 101  | 118  | 35    | 406   | 1    | 82   | 66   | 147  | 61    | 6542  | 127  | 1   | 82    | 935   | 401   | 182   | 2    | 130   | 1    | 131  | 19  |
| z | 191   | 94    | 0    | 0    | 3    | 227   | 0    | 1    | 2     | 124   | 0    | 34   | 6    | 2    | 5     | 55    | 0    | 0   | 1     | 2     | 3     | 27    | 0    | 1     | 0    | 96   | 132 |

## Appendix B

# Statistics on METU Turkish Corpus and Comparisons

**Table 6 The most used words, and comparison of 40.95 versus Turkish F and Turkish QWERTY keyboards**

|         |           | 40,95                  |               | F<br>(optimistic)      |            | QWERTY<br>(optimistic) |               |
|---------|-----------|------------------------|---------------|------------------------|------------|------------------------|---------------|
| Word    | Frequency | Distance<br>(diameter) | Time<br>(sec) | Distance<br>(diameter) | Time (sec) | Distance<br>(diameter) | Time<br>(sec) |
| bir     | 48798     | 2                      | 0,41          | 11,19                  | 1,1        | 6,83                   | 0,87          |
| ve      | 34469     | 1                      | 0,2           | 1,12                   | 0,22       | 2,83                   | 0,4           |
| bu      | 22905     | 1                      | 0,2           | 7,57                   | 0,63       | 2,24                   | 0,35          |
| da      | 19647     | 2,65                   | 0,38          | 1,8                    | 0,3        | 2                      | 0,32          |
| de      | 19468     | 1                      | 0,2           | 2,69                   | 0,38       | 1,12                   | 0,22          |
| için    | 10927     | 6,29                   | 0,97          | 12,87                  | 1,46       | 7,89                   | 1,14          |
| o       | 8100      | 0                      | 0             | 0                      | 0          | 0                      | 0             |
| çok     | 7899      | 4,61                   | 0,65          | 4,93                   | 0,73       | 3,35                   | 0,57          |
| gibi    | 7289      | 4,65                   | 0,79          | 14,27                  | 1,41       | 8,35                   | 1,18          |
| ne      | 7053      | 1                      | 0,2           | 4,61                   | 0,51       | 4,47                   | 0,5           |
| daha    | 6840      | 6,11                   | 0,97          | 11,02                  | 1,32       | 12                     | 1,38          |
| ile     | 6466      | 3                      | 0,53          | 13                     | 1,19       | 8,38                   | 0,9           |
| ama     | 6105      | 2                      | 0,41          | 8                      | 0,95       | 13,15                  | 1,19          |
| olarak  | 5941      | 5                      | 1,02          | 17,99                  | 2,21       | 21,5                   | 2,25          |
| türkiye | 5893      | 14,94                  | 2,14          | 23,92                  | 2,52       | 25,73                  | 2,72          |
| sonra   | 5886      | 9,38                   | 1,35          | 10,3                   | 1,45       | 15,7                   | 1,83          |
| nin     | 5832      | 2                      | 0,41          | 11,18                  | 1,11       | 4,47                   | 0,69          |
| her     | 5073      | 5                      | 0,73          | 9,23                   | 1,01       | 4,64                   | 0,66          |
| kadar   | 5031      | 7,29                   | 1,17          | 9,3                    | 1,4        | 13,69                  | 1,64          |
| ın      | 4950      | 1                      | 0,2           | 4                      | 0,47       | 4,61                   | 0,51          |
| en      | 4902      | 1                      | 0,2           | 4,61                   | 0,51       | 4,47                   | 0,5           |
| olan    | 4719      | 4                      | 0,73          | 13,25                  | 1,49       | 14,71                  | 1,42          |
| ya      | 4663      | 2                      | 0,32          | 6                      | 0,57       | 4,61                   | 0,51          |
| in      | 4399      | 1                      | 0,2           | 5,59                   | 0,56       | 2,24                   | 0,35          |
| diye    | 4030      | 5,65                   | 0,91          | 18,64                  | 1,71       | 9,61                   | 1,24          |
| var     | 3818      | 3,65                   | 0,58          | 3,81                   | 0,61       | 6,33                   | 0,84          |

|          |      |       |      |       |      |       |      |
|----------|------|-------|------|-------|------|-------|------|
| dedi     | 3759 | 4     | 0,73 | 9,03  | 1,22 | 6,85  | 0,95 |
| iki      | 3746 | 5,29  | 0,76 | 10    | 1,06 | 2,24  | 0,44 |
| ise      | 3731 | 3,65  | 0,58 | 10,2  | 1,06 | 6,71  | 0,78 |
| ben      | 3722 | 3,65  | 0,58 | 10,2  | 1,06 | 8,08  | 0,95 |
| ki       | 3678 | 2,65  | 0,38 | 5     | 0,53 | 1,12  | 0,22 |
| değil    | 3520 | 7,73  | 1,23 | 11,93 | 1,44 | 13,92 | 1,58 |
| nın      | 3441 | 2     | 0,41 | 8     | 0,95 | 9,22  | 1,02 |
| büyük    | 3435 | 11,54 | 1,59 | 15,64 | 1,83 | 21,96 | 2,18 |
| a        | 3424 | 0     | 0    | 0     | 0    | 0     | 0    |
| yeni     | 3246 | 3     | 0,61 | 17,2  | 1,68 | 9,71  | 1,25 |
| içinde   | 3113 | 8,29  | 1,37 | 17,56 | 2,17 | 12,65 | 1,81 |
| olduğunu | 3002 | 17,9  | 2,56 | 29,62 | 3,27 | 22,76 | 2,84 |
| zaman    | 2903 | 7,61  | 1,18 | 14,33 | 1,78 | 19,86 | 1,97 |
| ilk      | 2871 | 3     | 0,53 | 9     | 0,94 | 2,8   | 0,51 |
| olduğu   | 2848 | 12,61 | 1,79 | 16,47 | 2,07 | 18,76 | 2,19 |
| önce     | 2824 | 5,73  | 0,94 | 10,79 | 1,3  | 7,24  | 1,08 |
| yüzde    | 2641 | 6,65  | 1,11 | 11,73 | 1,56 | 19,12 | 1,81 |
| yok      | 2602 | 2     | 0,41 | 8,28  | 0,94 | 4,12  | 0,63 |
| ancak    | 2561 | 8,46  | 1,29 | 11,36 | 1,53 | 18,28 | 1,96 |
| hiç      | 2498 | 6,11  | 0,82 | 10,22 | 1,05 | 4,63  | 0,7  |
| bile     | 2495 | 4     | 0,73 | 19,58 | 1,78 | 11,21 | 1,29 |
| göre     | 2481 | 6,61  | 0,98 | 10,35 | 1,3  | 10,03 | 1,2  |
| gün      | 2454 | 2     | 0,41 | 6,33  | 0,84 | 11,96 | 1,14 |
| genel    | 2453 | 5     | 0,94 | 17,02 | 1,89 | 18,21 | 1,98 |
| son      | 2440 | 6,65  | 0,85 | 6,61  | 0,86 | 9,4   | 0,99 |
| şey      | 2421 | 4,46  | 0,64 | 15    | 1,26 | 10,57 | 1,04 |
| iyi      | 2373 | 5,29  | 0,76 | 16    | 1,29 | 4     | 0,65 |
| mi       | 2284 | 2     | 0,32 | 6     | 0,57 | 2     | 0,32 |
| kendi    | 2264 | 6     | 1,06 | 14,25 | 1,76 | 18,31 | 2,02 |
| e        | 2245 | 0     | 0    | 0     | 0    | 0     | 0    |
| ye       | 2213 | 1     | 0,2  | 7     | 0,61 | 3     | 0,41 |
| yıl      | 2204 | 5,65  | 0,79 | 12,17 | 1,15 | 7,59  | 0,88 |
| aynı     | 2197 | 5     | 0,85 | 12,69 | 1,43 | 11,46 | 1,36 |
| başka    | 2192 | 6,73  | 1,15 | 18,61 | 2    | 22,61 | 2,12 |
| böyle    | 2130 | 8,93  | 1,29 | 20,57 | 1,98 | 16,82 | 1,91 |
| türk     | 2063 | 8,65  | 1,18 | 3,92  | 0,73 | 19,61 | 1,77 |
| istanbul | 2058 | 13,11 | 2,08 | 30,84 | 3,26 | 23,44 | 2,88 |
| oldu     | 2053 | 6,61  | 0,98 | 12,86 | 1,47 | 10,76 | 1,25 |
| bütün    | 2033 | 11,65 | 1,53 | 8,33  | 1,24 | 25,71 | 2,36 |
| 1        | 2032 | 0     | 0    | 0     | 0    | 0     | 0    |
| arasında | 1978 | 10,29 | 1,78 | 21,3  | 2,82 | 25,63 | 2,93 |
| ırak     | 1968 | 4     | 0,73 | 8,69  | 1,2  | 17,26 | 1,63 |
| 3        | 1952 | 0     | 0    | 0     | 0    | 0     | 0    |
| nasıl    | 1949 | 8,29  | 1,29 | 17,34 | 1,96 | 17,59 | 1,76 |
| yer      | 1926 | 3     | 0,53 | 10,64 | 1,06 | 4     | 0,61 |
| başkanı  | 1923 | 9,73  | 1,67 | 26,25 | 2,93 | 32,81 | 3,18 |
| erdoğın  | 1922 | 17,34 | 2,36 | 13,08 | 1,94 | 24,85 | 2,55 |
| tek      | 1901 | 4,65  | 0,7  | 7     | 0,88 | 7,59  | 0,88 |

|          |      |       |      |       |      |       |      |
|----------|------|-------|------|-------|------|-------|------|
| abd      | 1881 | 5     | 0,73 | 8,22  | 0,96 | 7,3   | 0,89 |
| 2        | 1865 | 0     | 0    | 0     | 0    | 0     | 0    |
| mı       | 1851 | 3     | 0,41 | 4,61  | 0,51 | 3,64  | 0,45 |
| bin      | 1840 | 2     | 0,41 | 12,17 | 1,15 | 5,06  | 0,74 |
| doğru    | 1828 | 10,87 | 1,47 | 12,59 | 1,56 | 17,59 | 1,9  |
| şimdi    | 1818 | 10,46 | 1,5  | 21,33 | 2,09 | 13,91 | 1,72 |
| hem      | 1814 | 5,65  | 0,79 | 10,59 | 1,08 | 9,03  | 1    |
| karşı    | 1808 | 8     | 1,21 | 17,87 | 1,93 | 17,27 | 1,8  |
| ilgili   | 1784 | 11,65 | 1,76 | 29,68 | 2,69 | 12,1  | 1,77 |
| artık    | 1767 | 9,8   | 1,39 | 10,14 | 1,44 | 13,27 | 1,59 |
| söyledi  | 1751 | 11,11 | 1,76 | 25,9  | 2,77 | 26,13 | 2,82 |
| bana     | 1732 | 6     | 0,97 | 11,89 | 1,41 | 15,79 | 1,62 |
| önemli   | 1729 | 9,65  | 1,56 | 22,99 | 2,4  | 15,46 | 1,98 |
| birlikte | 1723 | 12,02 | 1,99 | 29,88 | 3,24 | 20,98 | 2,72 |
| milyon   | 1718 | 8,65  | 1,44 | 22,59 | 2,35 | 13,27 | 1,88 |
| eski     | 1676 | 8,9   | 1,21 | 10,73 | 1,26 | 8,24  | 1,01 |
| onu      | 1675 | 5,29  | 0,76 | 9,58  | 1    | 4,83  | 0,72 |
| benim    | 1675 | 6,65  | 1,11 | 21,79 | 2,19 | 12,31 | 1,62 |
| kez      | 1664 | 4,65  | 0,7  | 7,64  | 0,93 | 7,83  | 0,9  |
| 5        | 1655 | 0     | 0    | 0     | 0    | 0     | 0    |
| onun     | 1636 | 7,94  | 1,14 | 16,15 | 1,6  | 6,83  | 1,04 |
| yine     | 1633 | 4,65  | 0,79 | 18,2  | 1,71 | 8,71  | 1,17 |
| uzun     | 1611 | 9,86  | 1,28 | 17,76 | 1,71 | 12,77 | 1,42 |
| çünkü    | 1605 | 11,61 | 1,53 | 6,93  | 1,15 | 13,66 | 1,7  |
| şu       | 1595 | 1,73  | 0,3  | 10    | 0,71 | 3,64  | 0,45 |
| üzerine  | 1594 | 8,65  | 1,52 | 23,89 | 2,78 | 24,14 | 2,58 |

Table 7 The most used character sequences of length two

|      |           | 40,95                  |               | F<br>(optimistic)      |               | QWERTY<br>(optimistic) |               |
|------|-----------|------------------------|---------------|------------------------|---------------|------------------------|---------------|
| Word | Frequency | Distance<br>(diameter) | Time<br>(sec) | Distance<br>(diameter) | Time<br>(sec) | Distance<br>(diameter) | Time<br>(sec) |
| n    | 282161    | 1                      | 0,2           | 3,04                   | 0,41          | 1,12                   | 0,22          |
| ar   | 234180    | 1                      | 0,2           | 2,69                   | 0,38          | 2,69                   | 0,38          |
| b    | 229019    | 1,73                   | 0,3           | 1,12                   | 0,22          | 1,12                   | 0,22          |
| e    | 227684    | 1                      | 0,2           | 2                      | 0,32          | 3,04                   | 0,41          |
| la   | 214453    | 1                      | 0,2           | 5                      | 0,53          | 8                      | 0,65          |
| an   | 207081    | 2                      | 0,32          | 3,64                   | 0,45          | 5,59                   | 0,56          |
| a    | 201606    | 1                      | 0,2           | 2                      | 0,32          | 2,24                   | 0,35          |
| er   | 193704    | 2                      | 0,32          | 3,64                   | 0,45          | 1                      | 0,2           |
| in   | 185301    | 1                      | 0,2           | 5,59                   | 0,56          | 2,24                   | 0,35          |
| le   | 183754    | 1                      | 0,2           | 6                      | 0,57          | 6,58                   | 0,6           |
| i    | 175896    | 1                      | 0,2           | 2,24                   | 0,35          | 3,04                   | 0,41          |
| de   | 158024    | 1                      | 0,2           | 2,69                   | 0,38          | 1,12                   | 0,22          |
| k    | 157373    | 1,73                   | 0,3           | 2                      | 0,32          | 2                      | 0,32          |
| d    | 155971    | 1,73                   | 0,3           | 3,04                   | 0,41          | 2                      | 0,32          |
| en   | 149459    | 1                      | 0,2           | 4,61                   | 0,51          | 4,47                   | 0,5           |
| ın   | 147233    | 1                      | 0,2           | 4                      | 0,47          | 4,61                   | 0,51          |
| a    | 139492    | 1                      | 0,2           | 2                      | 0,32          | 2,24                   | 0,35          |
| da   | 134990    | 2,65                   | 0,38          | 1,8                    | 0,3           | 2                      | 0,32          |
| r    | 131168    | 1                      | 0,2           | 3,04                   | 0,41          | 3,04                   | 0,41          |
| y    | 127899    | 1,73                   | 0,3           | 2,83                   | 0,4           | 3,04                   | 0,41          |
| s    | 125667    | 2                      | 0,32          | 1,12                   | 0,22          | 2                      | 0,32          |
| ir   | 124643    | 1                      | 0,2           | 4,61                   | 0,51          | 4                      | 0,47          |
| ya   | 124296    | 2                      | 0,32          | 6                      | 0,57          | 4,61                   | 0,51          |
| ı    | 120405    | 1,73                   | 0,3           | 3,04                   | 0,41          | 3,61                   | 0,45          |
| ma   | 115887    | 1                      | 0,2           | 4                      | 0,47          | 6,58                   | 0,6           |
| g    | 114536    | 2,65                   | 0,38          | 3,35                   | 0,43          | 2                      | 0,32          |
| bi   | 113428    | 1                      | 0,2           | 6,58                   | 0,6           | 2,83                   | 0,4           |
| il   | 110711    | 2                      | 0,32          | 7                      | 0,61          | 1,8                    | 0,3           |
| ka   | 108598    | 1                      | 0,2           | 3                      | 0,41          | 7                      | 0,61          |
| nd   | 107252    | 1                      | 0,2           | 2                      | 0,32          | 3,64                   | 0,45          |
| k    | 105837    | 1,73                   | 0,3           | 2                      | 0,32          | 2                      | 0,32          |
| ra   | 105138    | 1                      | 0,2           | 2,69                   | 0,38          | 2,69                   | 0,38          |
| i    | 101924    | 1                      | 0,2           | 2,24                   | 0,35          | 3,04                   | 0,41          |
| ak   | 99851     | 1                      | 0,2           | 3                      | 0,41          | 7                      | 0,61          |
| al   | 99613     | 1                      | 0,2           | 5                      | 0,53          | 8                      | 0,65          |
| ri   | 99492     | 1                      | 0,2           | 4,61                   | 0,51          | 4                      | 0,47          |
| di   | 95575     | 2                      | 0,32          | 3,64                   | 0,45          | 4,61                   | 0,51          |
| li   | 95135     | 2                      | 0,32          | 7                      | 0,61          | 1,8                    | 0,3           |
| o    | 89435     | 2                      | 0,32          | 3,04                   | 0,41          | 3,04                   | 0,41          |
| ni   | 81415     | 1                      | 0,2           | 5,59                   | 0,56          | 2,24                   | 0,35          |
| me   | 81141     | 2,65                   | 0,38          | 5                      | 0,53          | 5,39                   | 0,55          |
| t    | 80333     | 2                      | 0,32          | 2                      | 0,32          | 3,04                   | 0,41          |
| el   | 80087     | 1                      | 0,2           | 6                      | 0,57          | 6,58                   | 0,6           |
| rı   | 77877     | 2                      | 0,32          | 3                      | 0,41          | 7,57                   | 0,63          |
| nl   | 76215     | 1                      | 0,2           | 4                      | 0,47          | 4,61                   | 0,51          |
| ay   | 74790     | 2                      | 0,32          | 6                      | 0,57          | 4,61                   | 0,51          |
| ek   | 74790     | 2                      | 0,32          | 4                      | 0,47          | 5,59                   | 0,56          |
| or   | 74731     | 2,65                   | 0,38          | 2                      | 0,32          | 5                      | 0,53          |

|    |       |      |      |      |      |      |      |
|----|-------|------|------|------|------|------|------|
| ta | 74456 | 1    | 0,2  | 2    | 0,32 | 3,64 | 0,45 |
| ne | 73149 | 1    | 0,2  | 4,61 | 0,51 | 4,47 | 0,5  |
| ol | 71203 | 1    | 0,2  | 4,61 | 0,51 | 1,12 | 0,22 |
| ba | 67569 | 2    | 0,32 | 4,61 | 0,51 | 4,61 | 0,51 |
| si | 67202 | 1    | 0,2  | 5,59 | 0,56 | 5,59 | 0,56 |
| sa | 67089 | 2,65 | 0,38 | 3,64 | 0,45 | 1    | 0,2  |
| re | 67065 | 2    | 0,32 | 3,64 | 0,45 | 1    | 0,2  |
| e  | 66856 | 1    | 0,2  | 2    | 0,32 | 3,04 | 0,41 |
| ki | 66260 | 2,65 | 0,38 | 5    | 0,53 | 1,12 | 0,22 |
| h  | 66139 | 2,65 | 0,38 | 3,04 | 0,41 | 2    | 0,32 |
| am | 64844 | 1    | 0,2  | 4    | 0,47 | 6,58 | 0,6  |
| te | 64485 | 2,65 | 0,38 | 3    | 0,41 | 2    | 0,32 |
| yo | 64407 | 1    | 0,2  | 5,59 | 0,56 | 3    | 0,41 |
| iy | 64329 | 2,65 | 0,38 | 8    | 0,65 | 2    | 0,32 |
| ye | 63333 | 1    | 0,2  | 7    | 0,61 | 3    | 0,41 |
| et | 63280 | 2,65 | 0,38 | 3    | 0,41 | 2    | 0,32 |
| ti | 63240 | 2,65 | 0,38 | 4    | 0,47 | 3    | 0,41 |
| un | 62460 | 2,65 | 0,38 | 6,58 | 0,6  | 2    | 0,32 |
| u  | 62323 | 2    | 0,32 | 2,83 | 0,4  | 3,04 | 0,41 |
| as | 62316 | 2,65 | 0,38 | 3,64 | 0,45 | 1    | 0,2  |
| v  | 62068 | 2    | 0,32 | 1,12 | 0,22 | 1,12 | 0,22 |
| lı | 61067 | 2,65 | 0,38 | 5,59 | 0,56 | 2    | 0,32 |
| sı | 60516 | 1    | 0,2  | 4,47 | 0,5  | 9    | 0,68 |
| dı | 60355 | 1,73 | 0,3  | 2    | 0,32 | 8    | 0,65 |
| na | 59735 | 2    | 0,32 | 3,64 | 0,45 | 5,59 | 0,56 |
| ve | 59001 | 1    | 0,2  | 1,12 | 0,22 | 2,83 | 0,4  |
| m  | 58220 | 1,73 | 0,3  | 2    | 0,32 | 1,12 | 0,22 |
| rd | 57620 | 2,65 | 0,38 | 1    | 0,2  | 1,12 | 0,22 |
| ad | 55699 | 2,65 | 0,38 | 1,8  | 0,3  | 2    | 0,32 |
| mi | 54117 | 2    | 0,32 | 6    | 0,57 | 2    | 0,32 |
| on | 53534 | 2,65 | 0,38 | 3    | 0,41 | 2,83 | 0,4  |
| at | 52608 | 1    | 0,2  | 2    | 0,32 | 3,64 | 0,45 |
| aş | 52479 | 1,73 | 0,3  | 7    | 0,61 | 9    | 0,68 |
| ge | 51883 | 2    | 0,32 | 1,8  | 0,3  | 2,69 | 0,38 |
| nl | 51815 | 1,73 | 0,3  | 1,8  | 0,3  | 2,69 | 0,38 |
| im | 51488 | 2    | 0,32 | 6    | 0,57 | 2    | 0,32 |
| ha | 51357 | 1,73 | 0,3  | 4,61 | 0,51 | 5    | 0,53 |
| tı | 50623 | 3,61 | 0,45 | 2,69 | 0,38 | 6,58 | 0,6  |
| kl | 50269 | 1    | 0,2  | 2    | 0,32 | 1    | 0,2  |
| bu | 49910 | 1    | 0,2  | 7,57 | 0,63 | 2,24 | 0,35 |
| em | 49881 | 2,65 | 0,38 | 5    | 0,53 | 5,39 | 0,55 |
| ıl | 49622 | 2,65 | 0,38 | 5,59 | 0,56 | 2    | 0,32 |
| ç  | 48276 | 2,65 | 0,38 | 1,12 | 0,22 | 1,8  | 0,3  |
| ed | 48262 | 1    | 0,2  | 2,69 | 0,38 | 1,12 | 0,22 |
| es | 47677 | 2,65 | 0,38 | 4,61 | 0,51 | 1,12 | 0,22 |
| ün | 46378 | 1    | 0,2  | 2,69 | 0,38 | 5,39 | 0,55 |
| ik | 46283 | 2,65 | 0,38 | 5    | 0,53 | 1,12 | 0,22 |
| ır | 46115 | 2    | 0,32 | 3    | 0,41 | 7,57 | 0,63 |
| se | 46104 | 2,65 | 0,38 | 4,61 | 0,51 | 1,12 | 0,22 |

**Table 8 The most used character sequences of length three**

|      |           | 40,95                  |               | F<br>(optimistic)      |               | QWERTY<br>(optimistic) |               |
|------|-----------|------------------------|---------------|------------------------|---------------|------------------------|---------------|
| Word | Frequency | Distance<br>(diameter) | Time<br>(sec) | Distance<br>(diameter) | Time<br>(sec) | Distance<br>(diameter) | Time<br>(sec) |
| lar  | 100428    | 2                      | 0,41          | 7,69                   | 0,91          | 10,69                  | 1,03          |
| bi   | 83699     | 2,73                   | 0,5           | 7,69                   | 0,82          | 3,95                   | 0,62          |
| ler  | 80275     | 3                      | 0,53          | 9,64                   | 1,02          | 7,58                   | 0,8           |
| an   | 69257     | 3                      | 0,53          | 6,68                   | 0,86          | 6,71                   | 0,78          |
| eri  | 67751     | 3                      | 0,53          | 8,25                   | 0,96          | 5                      | 0,68          |
| bir  | 66288     | 2                      | 0,41          | 11,19                  | 1,1           | 6,83                   | 0,87          |
| ya   | 64916     | 3,73                   | 0,62          | 8,83                   | 0,97          | 7,65                   | 0,92          |
| in   | 64455     | 2                      | 0,41          | 8,63                   | 0,97          | 3,35                   | 0,57          |
| arı  | 63779     | 3                      | 0,53          | 5,69                   | 0,79          | 10,26                  | 1,02          |
| ka   | 63356     | 2,73                   | 0,5           | 5                      | 0,73          | 9                      | 0,94          |
| en   | 62251     | 2                      | 0,41          | 7,65                   | 0,92          | 5,59                   | 0,72          |
| da   | 57360     | 3,65                   | 0,58          | 3,8                    | 0,63          | 4,24                   | 0,67          |
| ir   | 55901     | 2                      | 0,41          | 7,65                   | 0,92          | 7,04                   | 0,89          |
| de   | 54881     | 2,73                   | 0,5           | 5,73                   | 0,8           | 3,12                   | 0,54          |
| de   | 53380     | 2                      | 0,41          | 4,69                   | 0,71          | 4,16                   | 0,63          |
| ara  | 49265     | 2                      | 0,41          | 5,39                   | 0,77          | 5,39                   | 0,77          |
| ba   | 48456     | 3,73                   | 0,62          | 5,73                   | 0,73          | 5,73                   | 0,73          |
| ın   | 48123     | 2                      | 0,41          | 7,04                   | 0,89          | 5,73                   | 0,73          |
| ol   | 47481     | 3                      | 0,53          | 7,65                   | 0,92          | 4,16                   | 0,63          |
| ve   | 46793     | 3                      | 0,53          | 2,24                   | 0,44          | 3,95                   | 0,62          |
| nda  | 45063     | 3,65                   | 0,58          | 3,8                    | 0,63          | 5,64                   | 0,78          |
| yor  | 44544     | 3,65                   | 0,58          | 7,59                   | 0,88          | 8                      | 0,94          |
| ge   | 44037     | 4,65                   | 0,7           | 5,16                   | 0,74          | 4,69                   | 0,71          |
| bu   | 41538     | 2,73                   | 0,5           | 8,68                   | 0,85          | 3,35                   | 0,57          |
| ini  | 39313     | 2                      | 0,41          | 11,18                  | 1,11          | 4,47                   | 0,69          |
| ını  | 37303     | 2                      | 0,41          | 8                      | 0,95          | 9,22                   | 1,02          |
| ile  | 36850     | 3                      | 0,53          | 13                     | 1,19          | 8,38                   | 0,9           |
| ası  | 36001     | 3,65                   | 0,58          | 8,11                   | 0,95          | 10                     | 0,88          |
| rin  | 35581     | 2                      | 0,41          | 10,2                   | 1,06          | 6,24                   | 0,82          |
| ve   | 35293     | 2                      | 0,41          | 3,12                   | 0,54          | 5,87                   | 0,81          |
| nde  | 34157     | 2                      | 0,41          | 4,69                   | 0,71          | 4,76                   | 0,67          |
| n b  | 34101     | 2,73                   | 0,5           | 4,16                   | 0,63          | 2,24                   | 0,44          |
| sa   | 33079     | 4,65                   | 0,7           | 4,76                   | 0,67          | 3                      | 0,53          |
| lan  | 33027     | 3                      | 0,53          | 8,64                   | 0,98          | 13,59                  | 1,2           |
| le   | 32874     | 2                      | 0,41          | 8                      | 0,9           | 9,62                   | 1,01          |
| den  | 32352     | 2                      | 0,41          | 7,3                    | 0,89          | 5,59                   | 0,72          |
| da   | 32350     | 4,38                   | 0,68          | 4,84                   | 0,71          | 4                      | 0,65          |
| ha   | 31827     | 4,38                   | 0,68          | 7,65                   | 0,92          | 7                      | 0,85          |
| ama  | 31591     | 2                      | 0,41          | 8                      | 0,95          | 13,15                  | 1,19          |
| ınd  | 31513     | 2                      | 0,41          | 6                      | 0,8           | 8,25                   | 0,96          |
| rın  | 31447     | 3                      | 0,53          | 7                      | 0,88          | 12,18                  | 1,14          |
| anı  | 30563     | 3                      | 0,53          | 7,64                   | 0,93          | 10,2                   | 1,06          |
| ar   | 29922     | 2                      | 0,41          | 5,73                   | 0,8           | 5,73                   | 0,8           |
| ne   | 29893     | 2                      | 0,41          | 6,61                   | 0,83          | 7,51                   | 0,91          |
| esi  | 29004     | 3,65                   | 0,58          | 10,2                   | 1,06          | 6,71                   | 0,78          |
| ak   | 28904     | 2,73                   | 0,5           | 5                      | 0,73          | 9                      | 0,94          |
| er   | 28753     | 3                      | 0,53          | 6,68                   | 0,86          | 4,04                   | 0,62          |

|     |       |      |      |       |      |       |      |
|-----|-------|------|------|-------|------|-------|------|
| ni  | 28001 | 2    | 0,41 | 7,83  | 0,9  | 5,28  | 0,76 |
| be  | 27950 | 4,38 | 0,68 | 6,71  | 0,78 | 4,72  | 0,67 |
| nla | 27797 | 2,73 | 0,5  | 6,8   | 0,83 | 10,69 | 1,03 |
| e b | 27596 | 2,73 | 0,5  | 3,12  | 0,54 | 4,16  | 0,63 |
| nı  | 27494 | 2,73 | 0,5  | 7,04  | 0,89 | 8,22  | 0,96 |
| ta  | 27300 | 3    | 0,53 | 4     | 0,65 | 6,68  | 0,86 |
| edi | 27140 | 3    | 0,53 | 6,33  | 0,84 | 5,73  | 0,73 |
| aya | 27074 | 4    | 0,65 | 12    | 1,15 | 9,22  | 1,02 |
| ind | 26392 | 2    | 0,41 | 7,59  | 0,88 | 5,88  | 0,8  |
| gö  | 26189 | 3,65 | 0,58 | 5,59  | 0,78 | 5,64  | 0,78 |
| ele | 25844 | 2    | 0,41 | 12    | 1,15 | 13,15 | 1,19 |
| dan | 25419 | 4,65 | 0,7  | 5,44  | 0,76 | 7,59  | 0,88 |
| a b | 25338 | 2,73 | 0,5  | 3,12  | 0,54 | 3,35  | 0,57 |
| nin | 25317 | 2    | 0,41 | 11,18 | 1,11 | 4,47  | 0,69 |
| ki  | 25138 | 3,65 | 0,58 | 7,24  | 0,87 | 4,16  | 0,63 |
| nın | 25037 | 2    | 0,41 | 8     | 0,95 | 9,22  | 1,02 |
| na  | 24886 | 3    | 0,53 | 5,64  | 0,78 | 7,83  | 0,9  |
| ala | 24817 | 2    | 0,41 | 10    | 1,06 | 16    | 1,29 |
| ili | 24598 | 4    | 0,65 | 14    | 1,22 | 3,61  | 0,61 |
| so  | 24441 | 6    | 0,8  | 4,72  | 0,67 | 8,58  | 0,92 |
| ola | 24395 | 2    | 0,41 | 9,61  | 1,04 | 9,12  | 0,87 |
| ko  | 24224 | 2,73 | 0,5  | 4,69  | 0,71 | 3,12  | 0,54 |
| eni | 24101 | 2    | 0,41 | 10,2  | 1,06 | 6,71  | 0,85 |
| iği | 23758 | 2    | 0,41 | 2     | 0,41 | 2,24  | 0,44 |
| ere | 23469 | 4    | 0,65 | 7,28  | 0,9  | 2     | 0,41 |
| sın | 23388 | 2    | 0,41 | 8,47  | 0,97 | 13,61 | 1,19 |
| anl | 22972 | 3,73 | 0,62 | 5,44  | 0,76 | 8,28  | 0,94 |
| eli | 22554 | 3    | 0,53 | 13    | 1,19 | 8,38  | 0,9  |
| bil | 22486 | 3    | 0,53 | 13,58 | 1,21 | 4,63  | 0,7  |
| ada | 22481 | 5,29 | 0,76 | 3,61  | 0,61 | 4     | 0,65 |
| kar | 22464 | 2    | 0,41 | 5,69  | 0,79 | 9,69  | 1    |
| bu  | 22449 | 3    | 0,53 | 10,39 | 1,03 | 5,28  | 0,76 |
| iye | 22147 | 3,65 | 0,58 | 15    | 1,26 | 5     | 0,73 |
| i b | 22135 | 2,73 | 0,5  | 3,35  | 0,57 | 4,16  | 0,63 |
| n d | 21825 | 2,73 | 0,5  | 6,08  | 0,82 | 3,12  | 0,54 |
| al  | 21707 | 2    | 0,41 | 7     | 0,85 | 10,24 | 0,99 |
| yle | 21700 | 2    | 0,41 | 7     | 0,78 | 10,22 | 1,05 |
| se  | 21603 | 4,65 | 0,7  | 5,73  | 0,73 | 3,12  | 0,54 |
| ine | 21541 | 2    | 0,41 | 10,2  | 1,06 | 6,71  | 0,85 |
| sin | 21513 | 2    | 0,41 | 11,18 | 1,11 | 7,83  | 0,9  |
| kla | 21481 | 2    | 0,41 | 7     | 0,85 | 9     | 0,85 |
| n k | 21432 | 2,73 | 0,5  | 5,04  | 0,73 | 3,12  | 0,54 |
| ri  | 21139 | 2    | 0,41 | 6,85  | 0,85 | 7,04  | 0,89 |
| n a | 21045 | 2    | 0,41 | 5,04  | 0,73 | 3,35  | 0,57 |
| alı | 21036 | 3,65 | 0,58 | 10,59 | 1,08 | 10    | 0,97 |
| baş | 20977 | 3,73 | 0,62 | 11,61 | 1,12 | 13,61 | 1,19 |
| iği | 20576 | 3,46 | 0,59 | 2,24  | 0,44 | 6     | 0,82 |
| ek  | 20429 | 3,73 | 0,62 | 6     | 0,8  | 7,59  | 0,88 |

Table 9 The most used character sequences of length four

|      |           | 40,95                  |               | F<br>(optimistic)      |               | QWERTY<br>(optimistic) |               |
|------|-----------|------------------------|---------------|------------------------|---------------|------------------------|---------------|
| Word | Frequency | Distance<br>(diameter) | Time<br>(sec) | Distance<br>(diameter) | Time<br>(sec) | Distance<br>(diameter) | Time<br>(sec) |
| bir  | 60949     | 3,73                   | 0,7           | 12,3                   | 1,32          | 7,95                   | 1,09          |
| bir  | 50404     | 3                      | 0,61          | 14,23                  | 1,52          | 9,87                   | 1,28          |
| ları | 48837     | 4                      | 0,73          | 10,69                  | 1,32          | 18,26                  | 1,66          |
| leri | 43967     | 4                      | 0,73          | 14,25                  | 1,53          | 11,58                  | 1,27          |
| ve   | 34196     | 4                      | 0,73          | 4,24                   | 0,77          | 6,99                   | 1,03          |
| erin | 31800     | 4                      | 0,73          | 13,84                  | 1,51          | 7,24                   | 1,02          |
| arın | 30574     | 4                      | 0,73          | 9,69                   | 1,27          | 14,87                  | 1,52          |
| ında | 30292     | 4,65                   | 0,79          | 7,8                    | 1,1           | 10,25                  | 1,28          |
| inde | 24326     | 3                      | 0,61          | 10,28                  | 1,26          | 6,99                   | 1,02          |
| nda  | 23558     | 4,65                   | 0,79          | 5,8                    | 0,95          | 7,88                   | 1,12          |
| nin  | 22705     | 3                      | 0,61          | 14,22                  | 1,52          | 5,59                   | 0,91          |
| den  | 21957     | 3                      | 0,61          | 10,34                  | 1,3           | 6,71                   | 0,94          |
| dan  | 21094     | 5,65                   | 0,91          | 8,48                   | 1,17          | 8,71                   | 1,1           |
| bu   | 20680     | 4,73                   | 0,82          | 11,51                  | 1,25          | 6,4                    | 0,98          |
| nın  | 19944     | 3                      | 0,61          | 11,04                  | 1,36          | 10,34                  | 1,24          |
| ini  | 19684     | 3                      | 0,61          | 13,42                  | 1,46          | 7,51                   | 1,1           |
| baş  | 19008     | 5,46                   | 0,92          | 12,73                  | 1,34          | 14,73                  | 1,41          |
| ını  | 18856     | 3,73                   | 0,7           | 11,04                  | 1,36          | 12,83                  | 1,47          |
| iyor | 18421     | 6,29                   | 0,97          | 15,59                  | 1,53          | 10                     | 1,26          |
| ola  | 18235     | 4                      | 0,73          | 12,65                  | 1,45          | 12,16                  | 1,28          |
| nlar | 18111     | 3,73                   | 0,7           | 9,5                    | 1,22          | 13,39                  | 1,42          |
| ine  | 17731     | 3                      | 0,61          | 12,2                   | 1,39          | 9,75                   | 1,26          |
| eri  | 17707     | 4                      | 0,73          | 10,49                  | 1,31          | 8,04                   | 1,09          |
| arı  | 17300     | 4,73                   | 0,82          | 8,73                   | 1,2           | 13,86                  | 1,47          |
| nde  | 17263     | 3                      | 0,61          | 6,69                   | 1,03          | 7,8                    | 1,08          |
| içi  | 16755     | 6,29                   | 0,97          | 9,52                   | 1,25          | 8,7                    | 1,2           |
| anla | 16466     | 4,73                   | 0,82          | 10,44                  | 1,28          | 16,28                  | 1,59          |
| lar  | 16222     | 3                      | 0,61          | 10,73                  | 1,32          | 13,73                  | 1,44          |
| için | 15949     | 6,29                   | 0,97          | 12,87                  | 1,46          | 7,89                   | 1,14          |
| asın | 15500     | 4,65                   | 0,79          | 12,11                  | 1,43          | 14,61                  | 1,39          |
| yap  | 15418     | 5,73                   | 0,94          | 14,42                  | 1,52          | 16,21                  | 1,58          |
| kar  | 15286     | 3,73                   | 0,7           | 7,69                   | 1,12          | 11,69                  | 1,32          |
| da   | 14625     | 5,38                   | 0,88          | 6,84                   | 1,04          | 6,24                   | 0,99          |
| iler | 14541     | 5                      | 0,85          | 16,64                  | 1,64          | 9,38                   | 1,1           |
| ıyor | 14511     | 6,65                   | 0,99          | 14,17                  | 1,47          | 13,59                  | 1,49          |
| de   | 14465     | 3,73                   | 0,7           | 7,73                   | 1,12          | 6,16                   | 0,96          |
| gör  | 14082     | 7,25                   | 1,03          | 10,06                  | 1,28          | 11,03                  | 1,32          |
| alar | 13852     | 3                      | 0,61          | 12,69                  | 1,44          | 18,69                  | 1,68          |
| n bi | 13599     | 3,73                   | 0,7           | 10,74                  | 1,23          | 5,06                   | 0,84          |
| ler  | 13500     | 4                      | 0,73          | 12,68                  | 1,44          | 10,62                  | 1,21          |
| klar | 13480     | 3                      | 0,61          | 9,69                   | 1,24          | 11,69                  | 1,24          |
| ına  | 13387     | 4                      | 0,73          | 9,64                   | 1,25          | 12,44                  | 1,41          |
| ması | 13130     | 4,65                   | 0,79          | 12,11                  | 1,43          | 16,58                  | 1,48          |
| eler | 13110     | 4                      | 0,73          | 15,64                  | 1,6           | 14,15                  | 1,4           |
| inin | 13107     | 3                      | 0,61          | 16,77                  | 1,67          | 6,71                   | 1,04          |
| endi | 13009     | 4                      | 0,73          | 10,25                  | 1,28          | 12,72                  | 1,46          |
| gel  | 12932     | 5,65                   | 0,91          | 11,16                  | 1,31          | 11,27                  | 1,3           |
| son  | 12899     | 8,65                   | 1,18          | 7,72                   | 1,08          | 11,4                   | 1,31          |

|      |       |      |      |       |      |       |      |
|------|-------|------|------|-------|------|-------|------|
| lara | 12645 | 3    | 0,61 | 10,39 | 1,3  | 13,39 | 1,42 |
| ndan | 12205 | 5,65 | 0,91 | 7,44  | 1,08 | 11,23 | 1,33 |
| öyle | 12023 | 5,46 | 0,85 | 14,57 | 1,41 | 13,82 | 1,5  |
| esin | 11981 | 4,65 | 0,79 | 15,79 | 1,62 | 8,94  | 1,12 |
| ının | 11809 | 3    | 0,61 | 12    | 1,42 | 13,83 | 1,52 |
| bil  | 11521 | 4,73 | 0,82 | 14,69 | 1,43 | 5,75  | 0,92 |
| yle  | 11519 | 3    | 0,61 | 9     | 1,1  | 13,26 | 1,46 |
| ası  | 11456 | 5,38 | 0,88 | 11,15 | 1,36 | 13,61 | 1,33 |
| lan  | 11270 | 4    | 0,73 | 11,68 | 1,39 | 14,71 | 1,42 |
| rini | 11269 | 3    | 0,61 | 15,79 | 1,62 | 8,47  | 1,17 |
| diği | 11137 | 3,73 | 0,7  | 4     | 0,73 | 10,24 | 1,09 |
| kon  | 10949 | 5,38 | 0,88 | 7,69  | 1,12 | 5,95  | 0,94 |
| oldu | 10944 | 6,61 | 0,98 | 12,86 | 1,47 | 10,76 | 1,25 |
| arak | 10926 | 3    | 0,61 | 8,39  | 1,18 | 12,39 | 1,38 |
| rını | 10913 | 4    | 0,73 | 11    | 1,36 | 16,79 | 1,65 |
| rak  | 10768 | 3,73 | 0,7  | 7,69  | 1,12 | 11,69 | 1,32 |
| ara  | 10608 | 3    | 0,61 | 7,39  | 1,09 | 7,62  | 1,12 |
| değ  | 10526 | 5,73 | 0,91 | 6,85  | 1,02 | 11,12 | 1,19 |
| tür  | 10428 | 8,65 | 1,18 | 4,8   | 0,83 | 18,04 | 1,67 |
| ver  | 10377 | 5    | 0,85 | 5,88  | 0,89 | 4,95  | 0,82 |
| old  | 10320 | 5    | 0,85 | 11,29 | 1,37 | 10,16 | 1,21 |
| ger  | 10305 | 6,65 | 1,03 | 8,8   | 1,19 | 5,69  | 0,91 |
| çin  | 10186 | 4,65 | 0,79 | 12,27 | 1,42 | 6,18  | 0,96 |
| diği | 10146 | 5,46 | 0,92 | 5,88  | 0,89 | 10,61 | 1,32 |
| duğu | 10092 | 9,61 | 1,27 | 8,22  | 1,11 | 11,64 | 1,4  |
| dı.  | 10033 | 1,73 | 0,3  | 2     | 0,32 | 8     | 0,65 |
| türk | 10021 | 8,65 | 1,18 | 3,92  | 0,73 | 19,61 | 1,77 |
| rın  | 9934  | 4    | 0,73 | 10,04 | 1,29 | 13,29 | 1,36 |
| n ya | 9916  | 4,73 | 0,82 | 11,87 | 1,38 | 8,77  | 1,14 |
| iği  | 9879  | 3,73 | 0,7  | 5,04  | 0,82 | 5,84  | 0,89 |
| olm  | 9871  | 5    | 0,85 | 8,65  | 1,12 | 5,96  | 0,94 |
| e ka | 9782  | 3,73 | 0,7  | 7     | 1,06 | 12,04 | 1,35 |
| i bi | 9734  | 3,73 | 0,7  | 9,93  | 1,16 | 6,99  | 1,03 |
| a ka | 9722  | 3,73 | 0,7  | 7     | 1,06 | 11,24 | 1,28 |
| ist  | 9687  | 5,46 | 0,85 | 9,63  | 1,2  | 11,32 | 1,35 |
| ile  | 9604  | 4    | 0,73 | 15    | 1,51 | 11,42 | 1,31 |
| esi  | 9554  | 4,65 | 0,79 | 12,44 | 1,41 | 9,75  | 1,19 |
| kler | 9529  | 4    | 0,73 | 11,64 | 1,35 | 8,58  | 1    |
| an b | 9524  | 4,73 | 0,82 | 7,8   | 1,08 | 7,83  | 1    |
| acak | 9487  | 7,93 | 1,09 | 5,24  | 0,85 | 12,39 | 1,38 |
| aya  | 9465  | 5    | 0,85 | 14    | 1,47 | 11,46 | 1,36 |
| erek | 9451  | 6    | 0,97 | 11,28 | 1,38 | 7,59  | 0,96 |
| anın | 9312  | 4    | 0,73 | 11,64 | 1,4  | 14,81 | 1,57 |
| e ya | 9225  | 4,73 | 0,82 | 10,83 | 1,29 | 10,69 | 1,33 |

**Table 10** The most used character sequences of length five

|       |           | 40,95                  |               | F<br>(optimistic)      |               | QWERTY<br>(optimistic) |               |
|-------|-----------|------------------------|---------------|------------------------|---------------|------------------------|---------------|
| Word  | Frequency | Distance<br>(diameter) | Time<br>(sec) | Distance<br>(diameter) | Time<br>(sec) | Distance<br>(diameter) | Time<br>(sec) |
| bir   | 47677     | 4,73                   | 0,91          | 15,35                  | 1,74          | 10,99                  | 1,5           |
| ların | 27283     | 5                      | 0,94          | 14,69                  | 1,79          | 22,87                  | 2,17          |
| lerin | 24124     | 5                      | 0,94          | 19,84                  | 2,09          | 13,81                  | 1,62          |
| ında  | 15942     | 5,65                   | 0,99          | 9,8                    | 1,42          | 12,49                  | 1,63          |
| için  | 15705     | 7,29                   | 1,17          | 15,11                  | 1,8           | 10,93                  | 1,55          |
| ları  | 14872     | 5,73                   | 1,03          | 13,73                  | 1,73          | 21,86                  | 2,11          |
| inde  | 13632     | 4                      | 0,82          | 12,28                  | 1,59          | 10,04                  | 1,43          |
| leri  | 13458     | 5                      | 0,94          | 16,49                  | 1,88          | 14,62                  | 1,69          |
| inin  | 12230     | 4                      | 0,82          | 19,81                  | 2,08          | 7,83                   | 1,26          |
| ndan  | 11101     | 6,65                   | 1,11          | 10,48                  | 1,49          | 12,35                  | 1,55          |
| n bir | 11095     | 4,73                   | 0,91          | 15,35                  | 1,74          | 9,06                   | 1,31          |
| ının  | 11015     | 4                      | 0,82          | 15,04                  | 1,83          | 14,95                  | 1,74          |
| arını | 10720     | 5                      | 0,94          | 13,69                  | 1,74          | 19,48                  | 2,03          |
| oldu  | 10318     | 8,61                   | 1,3           | 15,9                   | 1,88          | 13,8                   | 1,66          |
| erini | 10104     | 5                      | 0,94          | 19,43                  | 2,07          | 9,47                   | 1,37          |
| için  | 10009     | 7,29                   | 1,17          | 15,91                  | 1,87          | 9,01                   | 1,36          |
| arın  | 9766      | 5                      | 0,94          | 12,73                  | 1,68          | 15,99                  | 1,75          |
| kları | 9453      | 5                      | 0,94          | 12,69                  | 1,64          | 19,26                  | 1,87          |
| nları | 8951      | 5,73                   | 1,03          | 12,5                   | 1,62          | 20,95                  | 2,05          |
| arak  | 8929      | 4,73                   | 0,91          | 10,39                  | 1,5           | 14,39                  | 1,7           |
| ından | 8729      | 6,65                   | 1,11          | 11,44                  | 1,55          | 15,84                  | 1,84          |
| konu  | 8724      | 8,02                   | 1,26          | 14,27                  | 1,71          | 7,95                   | 1,26          |
| olma  | 8708      | 6                      | 1,06          | 12,65                  | 1,6           | 12,54                  | 1,53          |
| türk  | 8574      | 10,65                  | 1,5           | 5,92                   | 1,05          | 22,65                  | 2,18          |
| anlar | 8558      | 5,73                   | 1,03          | 13,14                  | 1,67          | 18,98                  | 1,97          |
| sında | 8548      | 5,65                   | 0,99          | 12,27                  | 1,6           | 19,25                  | 1,96          |
| deği  | 8443      | 7,46                   | 1,2           | 7,97                   | 1,24          | 14,12                  | 1,6           |
| yordu | 8153      | 9,9                    | 1,42          | 13,2                   | 1,59          | 12,76                  | 1,61          |
| aları | 7820      | 5                      | 0,94          | 15,69                  | 1,85          | 26,26                  | 2,31          |
| gibi  | 7700      | 7,29                   | 1,17          | 17,63                  | 1,85          | 10,35                  | 1,5           |
| erin  | 7666      | 5                      | 0,94          | 16,88                  | 1,93          | 8,35                   | 1,24          |
| lduğu | 7592      | 11,61                  | 1,59          | 11,86                  | 1,57          | 17,64                  | 1,97          |
| çok   | 7533      | 8,98                   | 1,33          | 8,05                   | 1,27          | 7,16                   | 1,19          |
| kendi | 7462      | 6                      | 1,06          | 14,25                  | 1,76          | 18,31                  | 2,02          |
| nden  | 7366      | 4                      | 0,82          | 12,34                  | 1,63          | 10,35                  | 1,39          |
| ileri | 7256      | 6                      | 1,06          | 21,25                  | 2,14          | 13,38                  | 1,58          |
| kend  | 7240      | 5,73                   | 1,03          | 12,61                  | 1,63          | 15,7                   | 1,83          |
| eleri | 7237      | 5                      | 0,94          | 20,25                  | 2,11          | 18,15                  | 1,87          |
| i bir | 7193      | 4,73                   | 0,91          | 14,54                  | 1,67          | 10,99                  | 1,5           |
| rinde | 7178      | 4                      | 0,82          | 14,89                  | 1,77          | 10,99                  | 1,49          |
| olduğ | 7100      | 9,61                   | 1,39          | 14,66                  | 1,77          | 14,76                  | 1,72          |
| sonra | 7005      | 9,38                   | 1,35          | 10,3                   | 1,45          | 15,7                   | 1,83          |
| başka | 6979      | 6,73                   | 1,15          | 18,61                  | 2             | 22,61                  | 2,12          |
| a bir | 6932      | 4,73                   | 0,91          | 14,3                   | 1,65          | 10,18                  | 1,44          |
| e bir | 6809      | 4,73                   | 0,91          | 14,3                   | 1,65          | 10,99                  | 1,5           |
| sonr  | 6799      | 10,38                  | 1,47          | 8,72                   | 1,28          | 15,01                  | 1,76          |
| larak | 6777      | 4                      | 0,82          | 13,39                  | 1,7           | 20,39                  | 2,03          |
| daha  | 6770      | 7,84                   | 1,27          | 14,06                  | 1,73          | 14                     | 1,7           |

|       |      |       |      |       |      |       |      |
|-------|------|-------|------|-------|------|-------|------|
| erind | 6742 | 5     | 0,94 | 15,84 | 1,84 | 10,88 | 1,48 |
| daha  | 6724 | 7,11  | 1,18 | 13,02 | 1,64 | 14,24 | 1,72 |
| anla  | 6701 | 5,73  | 1,03 | 12,44 | 1,61 | 18,52 | 1,93 |
| yapı  | 6534 | 10,09 | 1,44 | 20,42 | 2,1  | 18,01 | 1,89 |
| larda | 6497 | 7,29  | 1,17 | 10,5  | 1,42 | 13,81 | 1,58 |
| kleri | 6415 | 5     | 0,94 | 16,25 | 1,86 | 12,58 | 1,48 |
| asınd | 6408 | 5,65  | 0,99 | 14,11 | 1,75 | 18,25 | 1,84 |
| başk  | 6400 | 7,46  | 1,24 | 16,73 | 1,81 | 16,73 | 1,73 |
| ile   | 6349 | 5     | 0,94 | 17,24 | 1,85 | 14,46 | 1,72 |
| olara | 6201 | 4     | 0,82 | 14,99 | 1,8  | 14,5  | 1,64 |
| daki  | 6172 | 7,29  | 1,17 | 12,04 | 1,58 | 13,16 | 1,57 |
| türki | 6170 | 11,29 | 1,56 | 8,92  | 1,26 | 20,73 | 1,99 |
| görü  | 6162 | 9,9   | 1,42 | 11,87 | 1,58 | 19,03 | 1,97 |
| rkiye | 6152 | 8,29  | 1,29 | 21,12 | 2,01 | 10,73 | 1,46 |
| ürkiy | 6149 | 9,94  | 1,47 | 15,92 | 1,7  | 15,73 | 1,7  |
| rini  | 6066 | 4     | 0,82 | 18,03 | 1,96 | 11,51 | 1,58 |
| erine | 6058 | 5     | 0,94 | 18,45 | 2,02 | 11,71 | 1,52 |
| rine  | 6013 | 4     | 0,82 | 16,81 | 1,89 | 13,75 | 1,73 |
| olar  | 5933 | 5     | 0,94 | 15,34 | 1,83 | 14,85 | 1,66 |
| olan  | 5881 | 6     | 1,06 | 16,29 | 1,9  | 17,75 | 1,83 |
| inden | 5873 | 4     | 0,82 | 14,89 | 1,77 | 11,47 | 1,52 |
| söyl  | 5862 | 9,11  | 1,35 | 14,68 | 1,58 | 15,82 | 1,82 |
| gibi  | 5857 | 5,65  | 0,99 | 16,51 | 1,76 | 11,39 | 1,59 |
| ması  | 5840 | 6,38  | 1,08 | 15,15 | 1,84 | 20,18 | 1,93 |
| rını  | 5808 | 5,73  | 1,03 | 14,04 | 1,77 | 20,39 | 2,1  |
| kara  | 5752 | 4,73  | 0,91 | 10,39 | 1,5  | 14,39 | 1,7  |
| karşı | 5727 | 8     | 1,21 | 17,87 | 1,93 | 17,27 | 1,8  |
| yorum | 5707 | 5,65  | 0,99 | 20,18 | 2,05 | 13,24 | 1,69 |
| karş  | 5705 | 5,73  | 1,03 | 12,3  | 1,62 | 18,27 | 1,92 |
| lerde | 5654 | 6,65  | 1,11 | 13,33 | 1,61 | 9,81  | 1,24 |
| iyle  | 5648 | 5,65  | 0,99 | 17    | 1,75 | 15,26 | 1,78 |
| a da  | 5580 | 6,38  | 1,08 | 8,84  | 1,36 | 8,47  | 1,34 |
| başl  | 5471 | 8,11  | 1,3  | 14,73 | 1,66 | 15,73 | 1,61 |
| söyle | 5440 | 8,11  | 1,23 | 19,57 | 1,94 | 20,4  | 2,09 |
| anın  | 5434 | 5     | 0,94 | 14,68 | 1,81 | 15,93 | 1,79 |
| ıgını | 5420 | 4     | 0,82 | 10    | 1,36 | 11,46 | 1,46 |
| ğını  | 5385 | 4,73  | 0,91 | 12,04 | 1,56 | 13,94 | 1,69 |
| diye  | 5382 | 7,38  | 1,2  | 21,68 | 2,12 | 11,61 | 1,56 |
| arınd | 5334 | 5     | 0,94 | 11,69 | 1,59 | 18,51 | 1,98 |
| rında | 5301 | 6,65  | 1,11 | 10,8  | 1,51 | 17,82 | 1,92 |
| iste  | 5292 | 8,11  | 1,23 | 12,63 | 1,61 | 13,32 | 1,67 |
| büyük | 5282 | 9,67  | 1,44 | 14,76 | 1,73 | 19,44 | 1,95 |
| deki  | 5266 | 6,65  | 1,11 | 13,93 | 1,73 | 10,87 | 1,41 |
| kada  | 5257 | 8,02  | 1,26 | 8,61  | 1,34 | 13    | 1,58 |
| masın | 5246 | 5,65  | 0,99 | 16,11 | 1,9  | 21,19 | 1,99 |