Performance and Usability of Flexible Membrane Keyboards

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ABSTRACT

Recently, many full-sized keyboards have been designed to fold in various ways in an attempt to make them more transportable. The flexible membrane keyboard, one type of full sized keyboard, is unique because it is made from silicon rubber, thus it is fully flexible and water resistant. Although a number of flexible keyboard characteristics are the same as standard keyboards (i.e. key size, shape and spacing), key-switch and key clicking mechanisms are inherently different. Since there is little or no existing research on flexible keyboards, there is a current need for data to facilitate design of such keyboards for use. Typing performance and perceived usability of several flexible keyboards that differed in terms of material hardness (hard, medium, or soft) and key contact point shape (circular or square) were studied. The results supported the hypothesis that both typing performance and usability of the flexible membrane keyboard were affected by material hardness and contact point shape. Square shaped contact points led to increased typing speed and decreased error rates, and medium or soft hardness led to increased typing speed. The best flexible keyboard (perceived by participants) in general received neutral usability ratings. However, ratings for mobility and design were much higher than neutral. Overall, subjective and objective measures of performance and usability indicated that flexible keyboards that are made of silicon of a soft or medium hardness and with a square shaped contact points are preferred.

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INTRODUCTION

Background

Since the first commercial typewriter was produced approximately 125 years ago, numerous studies to improve typing performance have been conducted (Hargreaves et al., 1992; Kroemer, 1992). Most studies related to keyboard operation have focused on work related musculoskeletal disorders (WMSDs) and keyboard layout to improve typing performance. Among the research community, there is an effort to redesign the keyboard itself, and as a result, several innovative keyboards (called alternative keyboards or ergonomic keyboards) have been introduced and studied (Nakaseko et al., 1985; Tittiranonda et al., 1999). Alternative keyboards have been shown to promote neutral wrist posture, but the scientific evidence regarding whether or not alternative keyboards prevent musculoskeletal disorders is inconclusive at this time (NIOSH, 1997). Keyboard design is a multidisciplinary area under discussion, and keyboards are still one of the most common input devices for computers.

Now we are in a ubiquitous computing era. Over 100 million computers were produced in 1999 (Miller & Freeman, 2000), along with 12.4 million mobile phones and 12.1 million personal digital assistants (PDA) in 2002 (American City Business Journals, 2003; Shim & Writer, 2003). These devices support personal network information systems. In the near future, almost all portable information equipment may be connected to a network through high-speed mobile communication network providers. A consequence of ubiquitous computing and the introduction of handheld electronic devices to the general public has been a need for a variety of input devices for communication. When designing a text input device for use during mobile computing, the device should incorporate the following features (Tang et al., 2001): (1) small size and portability, (2) operation in mobile environments (i.e. the user does not have to sit down at a platform in order to input text), (3) minimal need for visual and auditory attention, (4) easy to learn and use, and (5) physically robust. For handheld devices, a number of input methods have been developed such as built-in keyboards which are calculator-like keyboards (Dong & Vinson, 2003), on-screen keyboards called soft keyboards (Istance et al., 1996), thumb type keyboards, pen touch handwriting (Gelderen et al., 1993), as well as voice recognition (Su & Chung, 2001) and virtual input systems (Goette, 1998; Johnson et al., 1986). However, for high-speed data entry, full-sized keyboards are still the most efficient input devices for fast and accurate computer operation (Hahn, 2002). For this reason, highly-efficient and mobile data input devices are needed for the ubiquitous computing era. During the past few years, many full-sized keyboards have been designed to fold in various ways in an attempt to make them more transportable. The flexible membrane keyboard is one type of full sized keyboard, and it is unique among the other types because it is flexible and sealed from contamination, and thus water resistant. Many models of flexible membrane keyboards are commercially available.

Problem Statement

Like any other electromechanical device, keyboards can and do fail. When keyboards fail, the cause may be attributed to many things. Some causes, such as general abuse, breakage, and vandalism, are obvious; however, other possible causes are less obvious and often overlooked. Although computer keyboards do not generally fail due to airborne contamination (dirt and dust falling between the keys), if contaminants come to rest between two switch-contact points, the switch may be prevented from closing. Arita et al. (1981) and Verhaverbeke et al. (1991) found that switch failures include invasion of the switch cavity by airborne contaminants, and the formation of nonconductive metallic oxides on switch-contact points.

If the switch contact face is kept relatively clean and environmentally sealed, the introduction of outside contamination in the form of dust or lint should not be a concern. Flexible membrane keyboards are inherently sealed from airborne and liquid contaminants by the characteristics of their design. Nevertheless, using membrane keyboards is known to result in higher error rates and thus slower typing speed (Hahn, 2002). The main reason for errors is expected to be switch closing failure due to unstable contact between the circuit film and key switch-contact point. Two hypothesized reasons for this failure (1) key stiffness and (2) shape of key switch contact points. Key stiffness, or key resistance force, is a function of material softness (silicon) and key skirt characteristics such as thickness, length, and slope. The key skirt consists of a “force” slope around the edge of the silicon key top that collapses and provides tactile action, and the key skirt is also called the “rubber spring” (Figure 1) (Ramsey & Harrison, 2000).

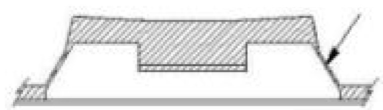


Figure 1. Section drawing of a key.

The shape of the key switch contact point is another important source of switch closing errors. Since the key top is only supported by the edge of the skirt, the key is often collapsed unparallel with the surface from pressing the corner of the key top, and this lateral key movement may result in switch closing errors. Details of switch-closing error are discussed in the method section.

Much of the research on usability of the standard keyboard and other types of data-entry devices has concentrated on typing performance, user satisfaction, and WMSDs (Goldstein et al., 1999; Shein et al., 1994). Little research has been conducted on the effects of key stiffness and key switch on typing performance and user satisfaction (Gerard et al., 1999; Watanabe & Kosaka, 1995). Yoshtake et al. (1997) studied typing performance and users' preference on four different keyboards, and found that keyboards with unclear tactile and auditory feedback tended to result in higher error rates than keyboards with clear tactile and auditory feedback, though no significant difference was found among the four keyboards in typing performance. With regard to preference, participants were divided into two groups: those who preferred keyboards with an unclear tactile feedback and no clicking sound, and those who preferred keyboards with a clear tactile feedback and clicking sound. They suggested that, “Suppliers of computer keyboards should provide two kinds of keyboards”. Gerard et al. (1999) studied the effects of key-switch stiffness on typing force and subjective discomfort level. A keyboard with an audible key click and a key activation force of 0.72 N and three keyboards with no key click that were the same in design but had different key activation forces (0.28 N, 0.56 N, and 0.83 N) were examined. They found that typing force was highest (as measured by EMG) for the 0.83 N keyboard and lowest for the 0.28 N and

0.72 N audible key click keyboards. Subjective discomfort was significantly higher for the keyboard with 0.83 N activation force. Most participants preferred the 0.72 N keyboard. The results of these two studies show that tactile feel, key-switch stiffness and auditory feedback affect user preference and typing performance.

Although a number of flexible keyboard characteristics are the same as standard keyboards (i.e. key size, shape and spacing), key-switch and key clicking mechanisms are inherently different from standard keyboards. Since there is little or no existing research on flexible keyboards, these differences in key design are hypothesized to contribute to higher error rates during flexible keyboard use. In order to provide evidence for improved design of flexible keyboards, usability studies of flexible keyboards are needed.

Objective of the Study

The objective of this study was to identify the effect of two characteristics of flexible keyboards, material hardness of the keyboard and the shape of the key switch-contact point, on typing performance and usability. The long-term goal of this study is to increase usability of the flexible keyboard. Results were used to generate design suggestions that can improve typing speed, reduce error rates, and maximize user satisfaction. A laboratory study was performed to assess usability of flexible keyboards through typing performance tests (Gross typing speed, Net typing speed, Error rate and types of errors) and usability questionnaires (Effectiveness, Efficiency, and Satisfaction). It was hypothesized that material hardness and key switch-contact point shape of the flexible membrane keyboard and their interaction would significantly affect typing performance (net typing speed, gross typing speed, error rate and error components) and usability (productivity, feedback feel, ease of use, ease of learn, and user satisfaction).

Focus of the study

Although many physical, psychosocial, and individual factors affect typing performance and user satisfaction, due to a limited availability of prototypes only two physical factors of the flexible keyboard were chosen for evaluation among several parameters (Table 1). Therefore, this study was limited to the effects of the hardness of the flexible membrane keyboard and the shape of the key switch-contact point on typing performance and usability. Other factors that might affect typing performance and usability (such as fatigue level, conditions of the workstation, and individual factors of participants, were not considered. Other peripheral tasks, such as filing, writing, and other activities were not evaluated. The use of other non-keyboard input devices (i.e. mouse, track ball, etc.) were not considered at this time.

Table 1. Design parameters of Flexible Keyboard.

Factor	Characteristic Description	Prototype Availability	Expected Effect
Keyboard surface	Coated	No	Touch feel Tactile feedback Pressure level Strike error Typing speed Fatigue
	Non-coated	Yes	
Key skirts (3 Factors)	Thickness	No	
	Slop	No	
	Length	No	
Stiffness of material (Silicon)	Soft	✓ Yes	
	Regular	✓ Yes	
	Stiff	✓ Yes	
Key switch-contact point	6 mm Circle	✓ Yes	Tactile feedback Strike error Signal error
	10mm Square	✓ Yes	
Circuit board switch-contact	6 mm Circle	No	Signal error
	10mm Square	Yes	
Keyboard Slope	0°	Yes	Fatigue
	7°	No	Strike error

✓ = Selected factor levels

LITERATURE REVIEW

There has been very little research, if any, on flexible keyboards. However, many studies have been conducted to determine the effect of keyboards or key characteristics (such as size, shape, texture, spacing, key-travel distance, activation force and feedback feel) on typing tasks for standard keyboards. These studies show a variety of approaches on how to investigate user preference, performance, operation, efficiency and effectiveness of keyboard design (Alden et al., 1972a; Butterbaugh & Rockwell, 1982; Cakir et al., 1980; Clare, 1976; Cumming, 1984; Deininger, 1960; Hansen, 1983; Kroemer, 1972; Monty & Snyder, 1983). Since the flexible membrane keyboard's key top size, shape, and spacing are the same as standard keyboards, in this section, common key characteristics are reviewed based on standard QWERTY keyboards. Although, these studies did not use flexible keyboards, due to the similarity of their characteristics, the methods and procedures of those studies were used to guide the present study.

Keyboards

The keyboard is one of the most essential components of human-computer interfaces in computer systems. Since a keyboard is a common interface between the user and the computer system, the design and construction of the keyboard is an important element, especially for someone who performs a substantial amount of typing. Design of the keyboard keys may affect user typing performance and productivity. Previous research indicates that poor keyboard design and use habits can lead to health issues for some people, WMSDs for example. Keyboard design parameters have been studied and established based on various approaches (Alden et al., 1972b; Bnesen, 1984; Conard & Hull, 1968; Goodman & Dickinson, 1983; Monty & Snyder, 1983). There are many studies on keyboard design issues such as key characteristics (caps and switches), arrangement of keys (layouts), key grouping (Klemmer, 1971), keyboard angle (Alden et al., 1972a; Woods, 2002) as well as internal keyboard circuitry (Ramsey & Harrison, 2000). Key characteristics are directly related to error rate, typing speed, and key strike force. Previous studies have verified that high finger forces while typing elevate the risk for musculoskeletal disorders of the upper extremities (Fagarasanu & Kumar, 2003; Rempel et al., 1991; Wu et al., 2003).

Flexible Keyboard

Membrane keyboards (Figure 2) are flexible because they are manufactured from silicon rubber and a thin polyester plastic sheet (film like) instead of a rigid PCB (Polychlorinated Biphenyl) panel. Flexible keyboards are currently used as external data input devices for conventional computers and handheld devices. They are also expected to be used in environments, such as industry, hospitals, restaurants, libraries, and marine and boating applications, or anywhere that dust and liquids are present. The keyboard provides portability as it can be rolled up without becoming crumpled, and maintains its original shape. The flexible nature of the keyboard enables it to be stored and rolled in many ways. For instance, it can be carried and connected to a PDA, cellular phone, laptop or any other handheld device when a high rate of input is required. Flexible membrane keyboards are also intended for use when protection from dust or liquid spills is important since the silicon-based material is impervious to most anything including water, coffee, even chemicals and cleaning solutions. However, efficiency of the flexible keyboards is known to be relatively poor, with flexible keyboards typically resulting in slower typing speeds and higher error rates than other full sized keyboards (Hahn, 2002). For this reason, user satisfaction levels may also be lower. One problem is that there are very few, if any, scientific studies on flexible membrane keyboards. Hence, usability and performance assessments are needed to enhance the design of flexible keyboards.

Figure 2. Example flexible keyboard (SoftKey^{TM}, MirTech Inc., 2002, Korea.).

Key Structure

Keycaps

Keycaps, also called "key tops", are the physical interface between users and keyboards. Keycaps are the surface of the keys that the user strikes with their fingers during typing. The role of the keycaps is that they connect key switches to the inner circuitry and send signals indicating which keys are hit. Keycaps play an important role in comfort when using the keyboard, because they are what users are actually operating with their fingers. Size, shape, and texture of the keycap are physical properties of keycaps, and spacing, alignment and travel distance are additional properties that may affect typing performance (Alden et al., 1972b; Butterbaugh & Rockwell, 1982; Cumming, 1984; Deininger, 1960; Hansen, 1983; Kroemer, 1972; Monty & Snyder, 1983). Flexible keyboards do not have separated keycaps because the keycap and key-switch are designed and manufactured as a single integrated unit. Flexible keyboard keys are inherently designed to not slip and have low reflection due to material (silicon rubber) characteristic.

Size

Most computer keyboard keycaps are the same size, approximately 12.7mm square on top, tapering to approximately 19mm at the bottom (Clare, 1976). There are some exceptions, for instance, non-standard keycap size and spacing are sometimes seen in small size laptop computers or specially designed keyboards for hand-held devices (Drury & Hoffmann, 1992; Loricchio & Lewis, 1991).

Shape

Almost all normal keycaps are shaped like truncated pyramids to protect the keyboard from contamination. Most standard keycaps are square since they provide more surface area within the same amount of space between keycap centers (Cakir et al., 1980).

Texture

The surfaces of normal keycaps are roughened (micro bumps), matte finished, and slightly concaved to improve traction, reduce finger slippage, and reduce glare from the surface. These designs do help hold the fingers and provide a visual cue, but over time the matte finished texturing is worn down, especially on the more frequently used keys. ANSI (1996) provides a more precise definition for specifying a reflectance limit and a measurement technique: when measured with a 60 degree gloss instrument or equivalent device, the specula reflectance (gloss) of key caps and visible surfaces shall be 45 percent or less.

Spacing

Center line distances between adjacent keys are recommended to be between 18 and 21 mm (0.71 and 0.82 inches) vertically , and between 18 and 19 mm (0.71 and 0.75 inches) horizontally (Alden et al., 1972b). The reason for standardized keycap size, spacing and alignment is simple: people learn the "feel" of typing on a keyboard and become used to its spacing and the size of keys. If someone who is used to typing on a particular keyboard uses a different keyboard with different-sized keys or different key spacing, slower typing speeds and higher error rates may occur. There is some evidence that a key spacing of less than 18mm substantially reduces typing speed (Blandel, 1990; Drury & Hoffmann, 1992; Wilund et al., 1987). However, there are still different special keys, such as the “Enter”, “Space Bar” and some function keys that often have different sizes, and spacing can vary between keyboard models, especially in laptop computers.

Key-switches

Translating motion of the fingers into text-based commands sent to the PC is the main role of the keyboard. In order to perform this task, the keyboard must have a way of detecting when keys are activated. This detection is done through the use of small devices called key-switches. A key-switch is used for each key on the keyboard. When the operator presses down on the keycap of a key, it pushes the key-switch down, causing the keyboard to register the key press. Regardless of design, all switches perform the same basic way, changing a flow of electricity in response to a stimulus.

In keyboards, key-switches must be designed to meet certain attributes (i.e. key travel, activation force, auditory feedback and tactile feedback) to ensure that they can be used reliably and comfortably over prolonged periods. Over the years, many different technologies have been used in building the key-switches used in computer keyboards.

Differences between these technology types can have an impact on the attributes of the keyboard, especially cost, durability, efficiency (functions, typing speed, error), and "feel" (Brunner et al., 1984). People may be able to immediately tell the difference between keyboards using different key-switch technologies just by using them for a few seconds.

Key-Travel and Activation Force

Key-travel, or the displacement of a key, is generated by the stroke of a key, and the range of travel varies depending on the switch mechanism. The activation force characteristic refers to how much pressure is required to cause the keycap to depress. Some key-switches are "softer" (less than 0.5N) and others "harder" (more than 1.0N). If very little force is required, other keys may be accidentally activated, or if too much force is required, some keys may fail to be activated because the user did not press hard enough. Moreover, excessive force induces finger fatigue. Optimum force characteristics of a key require a steadily increasing force as the key is depressed until contact is made (Alden et al., 1972b; Kinkead & Gonzales, 1969). Immediately beyond the switch-contact point, the force is substantially changed so that users can "feel" when the key has been pressed. Figure 3 shows a typical nonlinear relationship between key force and key displacement.

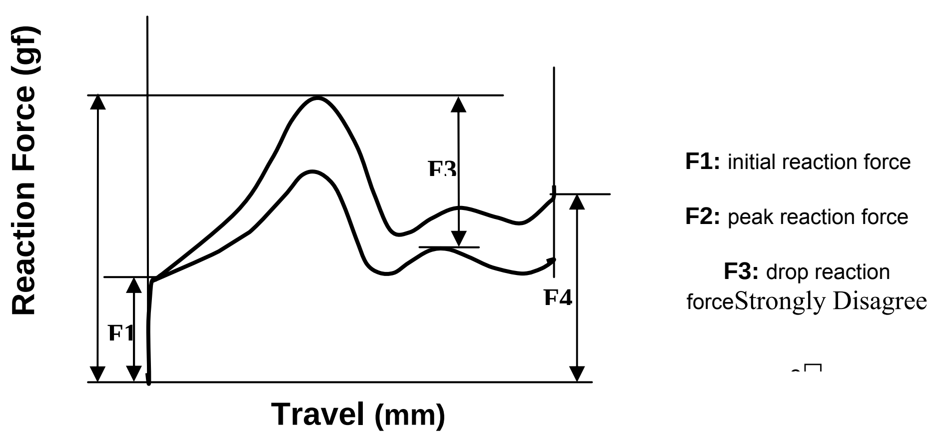


Figure 3. Travel and Reaction Force of a Switch (adapted from Kajiro, 1995).

ISO 9241-4 (1995) provides detailed information related to the static force and displacement characteristic of keyboard keys. Keys should have a maximum vertical displacement between 1.5 and 6.0 mm (0.06 and 0.24 inches) and the preferred displacement is between 2.0

and 4.0 mm (0.08 and 0.16 inches). The maximum force to depress the keys, expressed in Newtons (N), should be between 0.25N and 1.5N and ideally between 0.5N and 0.8N (ISO, 1995). Current high-production keyboards are in the range of 0.40 to 1. 25N with key displacements of 3 to 5 mm (Nagurka et al., 1999).

Feedback

Tactile feedback gives a typist the feeling of force when the fingers strike a key. Such feedback can be "high" or "low" based on the key-switch mechanisms (Armstrong et al., 1994). Tactile feedback provides a "click" feel and helps the typist subjectively register that a key has been activated. Tactile feedback, decided by key-switch characteristics, affects typing speed, error rate, and preference of users (Kinkead & Gonzales, 1969; Klemmer, 1971). For rapid typing, tactile feedback is important, because if the keyboard provides little or no feedback, most people cannot easily type rapidly.

Auditory Feedback refers to the sound made by a key as it completes a key-press. Some key-switches are much louder than others. Audibility is correlated with tactile feedback, and is used to provide feedback that a key has been pressed. The effect of auditory feedback on typing force, EMG, and comfort was studied by Gerard et al. (2002), who found that the introduction of enhanced auditory feedback caused a 10~20% reduction in 90th percentile typing force and finger flexor and extensor EMG. However, after one week of sporadic enhanced auditory feedback, there were no differences in typing force or EMG while participants were typing with or without the enhanced auditory feedback.

Feedback feel is the overall assessment of how the keyboard feels to the user. Someone who types a great deal can tell if they like a keyboard after typing a paragraph on it. This is an intangible aspect of the relation between the reaction forces of the keyboard switches and user key (switch) operation feeling, along with other design parameter attributes. According to one study about keyboard switch and Kansei (operator sensitivity) information, the most substantial factors of switch feeling, incorporating the concepts above, was expressed by the words "Clear", "Smooth", "Stiff", and "Clicking" among the 7 words (Table 2) to express operation feeling (Watanabe & Kosaka, 1995). Various other words that express operation feeling can be found in “A Universal Keyboard Switch for Feeling Test” (Kosaka et al., 1993).

Table 2. Definition of the words to express operation feeling.

Words	Meaning
Initially Smooth	One feels smooth when switch begins to move.
Smooth	One feels smooth in entire travel.
Deep	One feels deep when pushing the switches.
Stiffing	One feels stiff when pushing the switches.
Arriving Shock	One feels shock when switch arrives at the end.
Clear	One feels clear when pushing the switches.

(Adapted from Watanabe & Kosaka, 1995)

Usability

Usability is the measure of a user's experience when interacting with a product or system. The ISO 9241-11 (1998) definition of usability has been widely used and recognized and is good for understanding a broad perspective of usability. The definition has three separate aspects of usability, which are “Effectiveness”, “Efficiency” and “Satisfaction” (ISO, 1998). Effectiveness is the level to which a goal, or task, is achieved. Effectiveness can be assessed to examine task completion levels and outputs or results of quality. Efficiency is the amount of effort required to complete a goal. Although time, error rate and workload (mental and physical) to achieve a goal are some basic considerations of efficiency, measuring the contents of efficiency may vary based on different products. For instance, mobility is an important aspect of a laptop computer, while desktop computers do not require mobility. Finally, satisfaction is the level of comfort that the user feels when using a product or system (Jordan, 1998). Since satisfaction is the users’ attitude about a product, the simplest way to know how users feel about the product or system is to ask them whether they like or enjoy using it. Therefore, usability is a combination of factors that affect the user's experience with a product or system. Some common usability factors include: ease of learning, ease of use, ease of remembering, satisfaction, with a minimum number of errors, maximum output and minimum workload in shortest time.

In this study, several usability (or subjective) factors (productivity, ease of use, ease of learning (adaptability), mobility, design and satisfaction) and typing performance (or objective) factors (gross typing speed, net typing speed and number of errors) will be used to assess flexible keyboards

Usability Study of Keyboards

Many studies of computer input devices are aimed at alternative keyboards such as the ergonomic keyboard, onscreen-keyboard, pen-touch keyboard, virtual keyboard and non-keyboard input devices such as the mouse or trackball (Gelderen et al., 1993; Goldstein et al., 1999). There are some usability studies of key space, layout and tactile feel for standard keyboards. Fukuzumi & Kobayashi (2001) studied performance through subjective evaluations of personal computer keyboards. They studied three types of QWERTY keyboards and two kinds of M-system keyboards (linear type and ergonomic design type). According to the study, performance using traditional QWERTY keyboard was better than M-system keyboards, and ergonomic design keyboards (both M-system and QWERTY keyboards) had lower performance than any other keyboards. Yoshitake (1995) studied the relationship between key space and user performance on reduced keyboards for small computers to determine whether reducing the space occupied by keys affected the usability of the keyboard. A standard keyboard (a key space of 19.05 mm) and smaller keyboards with key spaces of 16.7, 16.0, 15.6, and 15.0 mm were compared. No performance degradation was found on keyboards with a key space of 16.7 mm (for faster typists capable of about 40 wpm), and 15.0 mm (for faster typists with narrow fingers). Other usability aspects of standard keyboards on tactile feel and key-switch stiffness are described in the problem statement (Section 1.2).

Summary

Key characteristics such as, size, key switch feel (tactile and auditory feedback) and layout are thought to contribute to the typing performance and usability of keyboards. Although most research has concentrated on determining the effect of key characteristics on typing performance and WMSDs, there is evidence that the characteristics affect user satisfaction independent of typing performance. No studies have investigated material hardness, or key-switch contact point shape when using flexible keyboards. The current research will identify the effects of selected factors on typing performance and usability in terms of productivity, easy of use, easy of learning, feedback feel and satisfaction.

METHOD

Experimental Design

A laboratory study was conducted to examine the effects of two selected factors on typing performance and usability of flexible membrane keyboards. Key switch-contact points (circle and square) and material hardness (soft, medium, hard) were evaluated using six flexible keyboard prototypes (Table 3). A 3-way mixed-factors design was used to quantify the main effects of the factor and gender on several dependent variables. The order of treatment conditions was counterbalanced using a pair of balanced Latin squares (one for each gender) for the 12 participants (6 females and 6 males).

Table 3. Treatment combinations.

Gender	**Switch-contact point**	**Hardness of material**		
		Soft	Medium	Hard
Male	6 mm Circle	t1	t2	t3
	10mm Square	t4	t5	t6
Female	6 mm Circle	t1	t2	t3
	10mm Square	t4	t5	t6

Description of variables

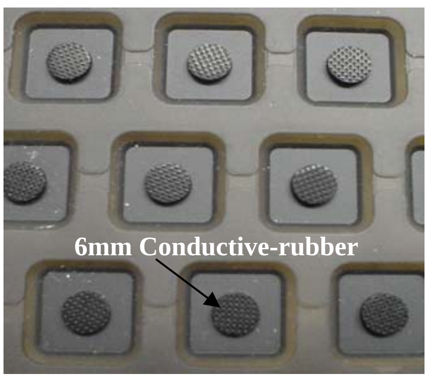
Independent Variables

There were three different levels of hardness for the keyboard (Table 4) and two different shapes of the key switch-contact point (Figure 4). The hardness of the silicon is one of the most important elements that affect the tactile feedback of keystrokes. The design of the key switch-contact point, made by conductive-rubber, is a crucial part of electronic signal transmission and it is directly related to switch closing error and thus likely to typing performance. Prototypes of flexible keyboards were tested and compared to each other. The six different flexible keyboard prototypes were provided by a manufacturer (Dong Hwan IND. & Krunis Co.) for experimental testing

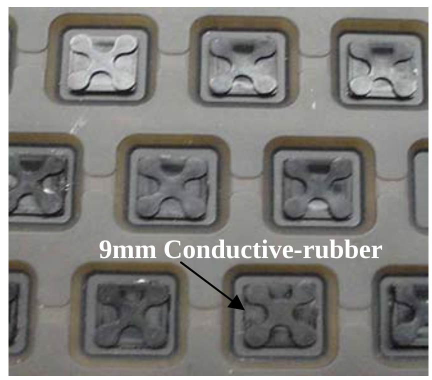
Table 4. Material Specification (Tensile Properties of SoftKey™)

Keyboard Hardness	Hardness Durometer A(°)	Tensile Strength Mpa(kgf/cm^2)	Ultimate elongation (%)
Soft	50°	6.0 (61)	300
Medium	55°	-	295
Hard	60°	7.0 (71)	290

This data provided by a prototype manufacturing company
(Dong Hwan IND. & Krunis Co., http://www.gomukorea.co.kr)



Circular Shape



Square Shape

Figure 4. Different shapes of key switch-contact point

As mentioned in the problem statement, the different key switch-contact point shapes (6 mm circular and 9 mm square) were expected to affect switch-closing error. Lateral key movement, caused by pressing the corner of the key top, may reduce the key travel distance and may the cause of an incomplete switch closing. The 9 mm square switch-contact point was expected to compensate for the reduced key travel distance by extending the contact region of the key switch-contact point (Figure 5).

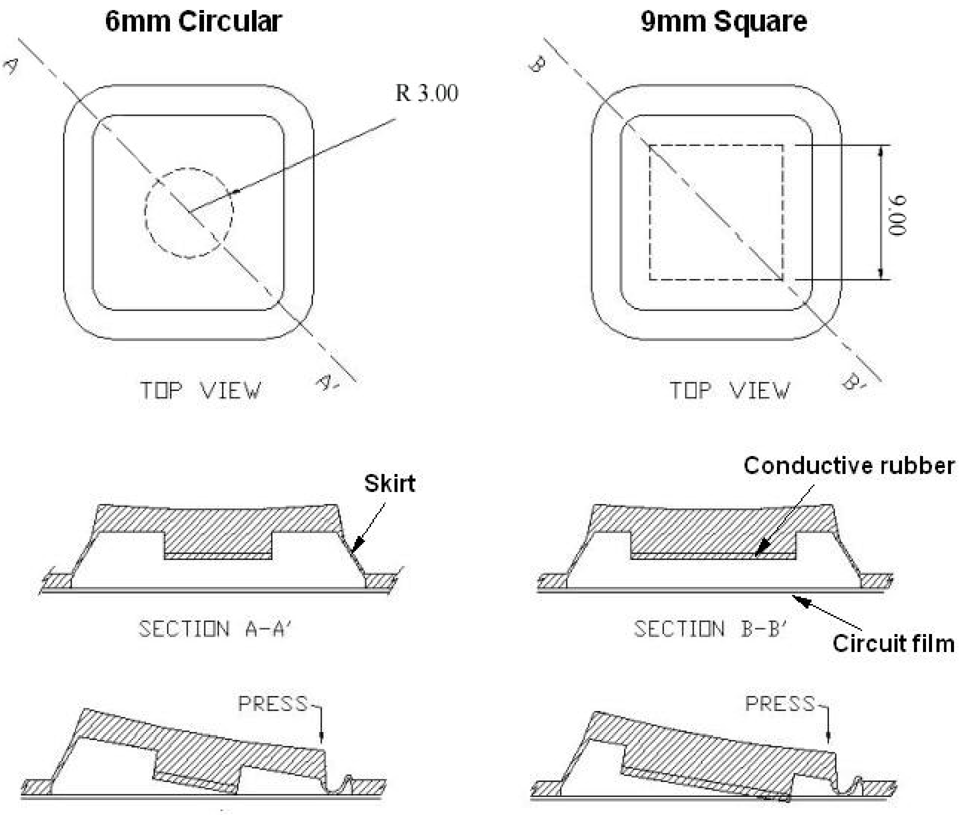


Figure 5. Unparallel Pressure Switch Operations

Dependent Variables

Both objective and subjective dependent variables were investigated. Objective measures included net typing speed, gross typing speed, numbers of errors and types of the errors, such as, missing words, miss spelled words, extra words, joint words, and split words (Table 5).

Typing performance was monitored using SkillCheck™ software (SkillCheck, Inc., Burlington, MA). In this study, net typing speed was considered the most valid measurement of a participant's typing speed over time because this value takes into accounts the participant's gross typing speed and number of errors.

Table 5. Typing test reports a variety of scoring details from SkillCheck™ manual V4.

Variable	Definition
Gross typing	The total number of keystrokes entered by the examinee divided by the number of minutes it took to complete the test.
Net typing	Gross data entry speed minus the number of errors.
Number of errors	The number of errors divided by the number of minutes the examinee made during the data entry test.
Missing Words	Data strings (text or numbers) the examinee left out when taking the test. Each omitted word or number is counted as a single error.
Misspelled Words	Data strings (text or numbers) entered incorrectly—this includes misspelled words and words with incorrect capitalization (for example, “oNe” instead of “one”). Incorrect spacing is also counted as a misspelling. For example, if you place two spaces between data (text or numbers), this is counted as a misspelling for the first data string (“word”).
Extra Words	Data strings (text or numbers) the examinee added when taking the test. Each added word or number is counted as a single error.
Joined Words	Data strings (text or numbers) entered correctly but with the space between the strings (“words”) missing are counted as a single error.
Split Words	Data strings (text or numbers) entered correctly but with an extra space within the strings (“words”) is counted as a single error.

Subjective measures were obtained using two questionnaires. A post-task questionnaire was used to assess user reactions for each flexible keyboard, and an exit questionnaire was used to assess the participants’ overall opinions/attitudes as to the best flexible keyboard (Appendix E). The post-task questionnaire consists of eight 5-point Likert-type scale questions, ranging from “strongly agree” to “strongly disagree”, and an open-ended question. Participants rated each keyboard in terms of effectiveness, efficiency, and satisfaction. Usability questions are summarized in Table 6 where questions are labeled by each category. The complete questionnaire can be found in Appendix D.

Table 6. Summary of Usability Questions (post-task questions).

Categories	Label No. (Question name)	List of questions
Productivity	Pr1 (effectiveness)	I can effectively type using this flexible keyboard.
	Pr2 (Usefulness)	The flexible keyboard is useful to type.
Feedback feel	Fb1 (Easy to push)	The flexible keyboard requires a little amount of force to push the key.
	Fb2 (Auditory FB)	I prefer the reduced key-clicking (typing) sound.
Easy of use	Eu1 (Time saving)	I believe this flexible keyboard saves me typing time.
	Eu2 (Easy to use)	This flexible keyboard is easy to use.
Easy of learning	El1 (Adaptability)	I can easily accommodate to this flexible keyboard.
	El2 (Easy to learn)	It is easy to learn to use this flexible keyboard.
Satisfaction	Sf1 (Comfortable)	My hand/fingers are comfortable when using this flexible keyboard.
	Sf2 (Satisfaction)	I am satisfied with the flexible keyboard

The exit questionnaire was given to participants after completing the test session each day. The exit questionnaire consisted of two parts. Part-I addressed general opinions including a rating of hardness and questions about reasons for preference; Part-II contained three ISO usability categories, which was divided into 7 sub-categories (productivity, ease of use, mobility, ease of learning, feedback feel, design and satisfaction). Participants were asked to rate the "best keyboard" for each question.

Task Description

Each participant completed two separate sessions (Day 1 and Day 2). In each session, participants had a 15-minute warm up period then performed 15 minutes of typing using each of six keyboards with 5 minutes of rest between each task. The time interval between day 1 and day 2 was between 24 and 48 hours to help standardize learning effects. An approved informed consent document, demographic and musculoskeletal questionnaires were given on day 1, and the post task questionnaires and an exit questionnaire were given on both day1 and day 2. Text passages from a technical communication book were inputted into the software (Randall 1996). Hard copies of the documents were displayed to participants on a paper holder located on the left side of the computer monitor. The length of each document was one page, and the font was double spaced and 12 point, Times New Roman. MS Office Word™ was used to qualify difficulty of the 14 separate documents (Table 7), and they were found comparable. Passages were presented to the participants randomly. The Flesch-Kincaid

Grade Level score rates text based on the U.S. high school grade level system , and the Flesch Reading Ease score is based on a 100 point scale; the higher the score, the easier it is to comprehend (Equation 1).

$$\textbf{Flesch Reading Ease} = 206.835 - (1.015 \times ASL) - (84.6 \times ASW)$$

$$\textbf{Flesch-Kincaid Grade Level} = (.39 \times ASL) + (11.8 \times ASW) - 15.59$$

Where, ASL = average sentence length (number of words divided by the number of sentences)
ASW = average number of syllables per word (number of syllables divided by number of words)

Equation 1. Flesch Score (Flesch Reading Ease and Flesch-Kincaid Grade Level).

Table 7. Flesch Reading Ease and Flesch-Kincaid Grade Level.

Documents Number	Number of Words	Reading Ease 0~100	Grade Level
1	464	27.6	12
2	455	32.4	12
3	460	21.0	12
4	445	26.0	12
5	434	26.9	12
6	421	26.6	12
7	439	26.9	12
8	428	25.3	12
9	469	27.7	12
10	416	30.6	12
11	451	28.1	12
12	457	33.2	12
13	425	20.8	12
14	420	28.1	12

If participants completed the passage before the end of a test, they continued typing from the start of the passage. Participants were not allowed to input numbers using the number pad. To make the test situation as similar to normal working conditions as possible, the tabletop, keyboard tray and chair height location and orientations were selected by participants for individual preference (Fernstrom & Ericson, 1997). The quality and quantity of the changed workstation position by self-selected procedure were not measured.

Equipment

SkillCheck™, a computer-based typing skills evaluation software program (V 4.0, SkillCheck, Inc., Burlington, MA), was used to administer the experimental typing tasks: a pre-typing task using a standard keyboard, and six typing tasks on two days. The software automatically recorded typing performance data during each task.

Six flexible keyboard prototypes (SoftKey™, MirTech Inc., Korea.) were used for the typing tasks. All keyboards for the tests are QWERTY type keyboards, and had the same features except for the two hypothesized factors. Specifications of flexible keyboard (hard hardness) are listed in Table 8.

Table 8. Specifications of Flexible keyboard (Hard hardness).

Number of Keys	106
Key-switch Technology	Silicon keypad with Carbon-Contact
Key Travel	1.2 mm / 0.05 Inch
Actuation Force	1.3 N
Key-switch Life	5 Million Operations
Electronic Interface	AT / PS2 (controller integrated)
Dimensions	18.1” x 5.8” x 0.3”
Weights	0.7Lbs
Operating Temperature	-10° C to 60° C / 14° F to 140° F

(MirTech Inc., A-607 Sigma2, 18 Kumi-Dong, Bundang-Ku, Sungnam-Si Korea)

A 17” CRT Monitor (Del E770s) was connected to a desktop computer (Dimension L866), Generation IV, and fully adjustable bi-level table (SIS Human Factor Technologies, Londonderry, NH) and a chair were arranged for the typing task. The chair has two adjustable armrests and a handle under the seat that can adjust the seat height.

Participants

In this study, 12 experienced typists, six females and six males, who use the 10-digit touch-typing method were recruited from the Virginia Tech (Blacksburg) population. The participants had a mean (SD) age of 22.8 (*SD*=2.6) years. The range of participants’ net typing speed was 36-57 words per minute, and the average were 47.25 (*SD*=7.23) words per minute detected using a standard keyboard. Participants reported using a computer keyboard at least 4 h/day or 20 h/week (Tittiranonda et al., 1999). Demographic information is summarized and listed in Appendix F.

Participants were screened using demographic and musculoskeletal questionnaires and results of a pre-experimental test. Participants with no prior experience in using any kind of flexible computer keyboard were selected to minimize the confounding effect of learning. The musculoskeletal questionnaire (Appendix C) was used to assess the presence of current hand or wrist MSDs and other potential confounding disorders caused by past medical history. All participants had no medical condition that could affect typing tasks, including arthritis, ache, pain and discomfort in the wrists, hands or fingers at any time during the last 12 months or currently (Kuorinka et al., 1987).

Procedure

Participants received a brief verbal and written description about the purpose of the study and a description of tests. Participants were asked to read and sign an approved informed consent document prior to data collection (Appendix A). After completing the demographic and musculoskeletal questionnaires (Appendix B, C), eligible participants were asked to move to the experimental computer workstation and adjust the table, keyboard tray, and chair to their desired preference. Participants were briefed on the SkillCheck™ software and took a 15-minute pre-typing task to assess net typing speed using a standard keyboard. If participants meet all criteria, anthropometric data was collected (Appendix B) and the testing session was begun. All treatment conditions were presented during the first session. While seated, the appropriate keyboard was placed on the keyboard tray and the participant was instructed to type each passage normally for each 15-minute task. A 5-minute rest period was provided between experimental conditions. During the rest period, the experimenter set up another keyboard for the next condition and performance data was recorded, and participants were asked to fill out the post task questionnaire (Appendix D). The same procedure was repeated for each experimental condition until all treatment conditions had been completed. The exit questionnaire (Appendix E) was presented when the participants had finished all of the experimental conditions. Total session time was approximately 2.5 to 3 hours per participant. Participants were compensated at a rate of $8 an hour.

Data processing and analysis

Appropriate descriptive statistics (i.e. means, standard deviations) were calculated for all defendant variables. The Shapiro-Wilk's normality test was conducted to determine whether the data fit a normal distribution and performed prior to subsequent analyses. A mixed-factor ANOVA was used to test the effects of trial order and independent variables on the dependent variables that met normality. The ANOVA results were considered significant at an alpha level of 0.05. Gender was a between-participants variable, while all the other independent variables were within-participants variables. A list of all the possible effects in ANOVA design is defined by the following structural model;

$$Y_{ijklmn} = \mu + \alpha_i + \beta_j + \delta_k + \phi_l + \gamma_{m(k)} + \alpha\beta_{ij} + \alpha\delta_{ik} + \alpha\phi_{il} + \beta\delta_{jk} + \beta\phi_{jl} + \delta\phi_{kl} + \alpha\beta\delta_{ijk} + \alpha\beta\phi_{ijl} + \alpha\delta\phi_{ikl} + \beta\delta\phi_{jkl} + \alpha\beta\delta\phi_{ijkl} + \tau_n + \varepsilon_{p(ijklmn)}$$

Where, Y_{ijklmn} = one of the observations in any one of the treatment groups

μ = grand mean of the treatment populations

α_i = effect of the hardness of flexible keyboard unit

β_j = effect of the switch-contact points shape

δ_k = gender effect

ϕ_l = day effect

$\gamma_{m(k)}$ = participant effect

$\alpha\beta_{ij}, \alpha\delta_{ik}, \ldots\ldots, \alpha\beta\delta\phi_{ijkl}$ = interactions between main effects

τ_n = order effect

$\varepsilon_{p(ijklmn)}$ = random error

Any significant differences found were analyzed using Tukey HSD tests as a post hoc analysis technique were appropriate to determine which levels produced significant differences.

Method

Pearson's correlation coefficients were calculated for all dependent variables to determine relationships. All variables had samples of $N = 144$, thus correlations were considered significant at $p \leq 0.01$, which corresponded approximately to $|r| \geq 0.254$ for $df = 142$. To determine the complementary relationship between objectives and subjective measure, a categorical analysis was performed in which NTS (a representative of objective measures) and all rating scores of each participant were compared for contact point shape and material hardness detailed descriptions of this analysis procedure are presented in Categorical analysis section.

RESULTS

Descriptive statistics for day, shape, hardness, and the interaction of shape and hardness for all dependent variables are presented in Appendix G. Ratings for subjective measures were treated as interval data and were included normality test. The results of normality tests shows some dependent measures were not normally distributed (Appendix H). However, the deviations were not substantial and thus, standard ANOVA was used as it is robust to non-normal data (Neter et al., 1996). Full ANOVA results and *p*-values for each objective and subjective measure are listed in Tables 9 and 10 respectively.

Table 9. ANOVA *p*-values of objective measures.

	NTS	GTS	ERR	MW	MSW	EW	JW	SW
gender	0.6909	0.7522	0.9771	0.6218	0.9394	0.7882	0.9005	0.7547
order	0.7762	0.2932	0.0920	0.3662	0.0834	0.5867	0.7439	0.3004
day	0.0016	0.9413	<.0001	0.0142	<.0001	0.1165	0.3452	0.0039
shape	<.0001	0.0135	0.0188	0.4958	0.0103	0.1165	0.6125	0.5062
hardness	<.0001	0.0003	0.2389	0.0005	0.1373	0.5741	0.0003	0.5174
day*shape	0.5697	0.8155	0.5848	0.5933	0.5194	0.5541	0.8131	0.2969
day*hardness	0.3309	0.2695	0.5969	0.9807	0.5553	0.6204	0.8039	0.2323
shape*hardness	0.0037	0.0054	0.8825	0.8300	0.7558	0.6576	0.2012	0.0813
day*shape*hardness	0.4541	0.5100	0.9583	0.4252	0.9172	0.3412	0.9827	0.7973
day*gender	0.2175	0.0662	0.1594	0.5435	0.1306	0.4305	0.6853	0.9243
shape*gender	0.8031	0.9447	0.7617	0.1032	0.2882	1.0000	0.0048	0.6347
day*shape*gender	0.4055	0.7099	0.4586	0.8683	0.3237	0.3248	0.5660	0.2181
hardness*gender	0.4675	0.2996	0.5188	0.4808	0.5288	0.2419	0.9111	0.7026
day*hardness*gender	0.1913	0.1816	0.8036	0.9338	0.8923	0.3684	0.5642	0.4174
shape*hardness*gender	0.7473	0.7284	0.9282	0.2735	0.8217	0.4056	0.3842	0.3029
day*shape*hardness*gender	0.3200	0.4307	0.9573	0.5491	0.9792	0.8807	0.8108	0.8417

Note: Highlighting indicates significant findings ($p < 0.05$)

NTS: Net typing speed, GTS: Gross typing speed, ERR: Error, MW: Missing words, MSW: Misspelled words, EW: Extra words, JW: Joined words, SW: Split words

Table 10. ANOVA *p*-values of subjective measures.

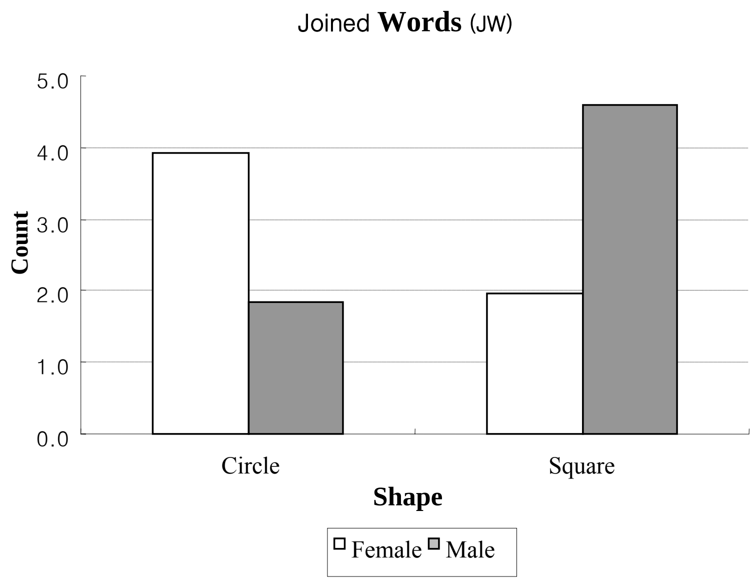
	Pr1	Pr2	Fb1	Fb2	Eu1	Eu2	El1	El2	Sf1	Sf2
gender	0.5029	0.7811	0.6789	0.7993	0.6666	0.6645	0.5243	0.3735	0.8427	0.8408
order	0.6115	0.5764	0.1323	0.1179	0.0022	0.1247	0.4054	0.6123	0.7569	0.1334
day	0.0324	0.0001	0.9341	0.8443	0.0003	0.0011	0.0027	0.0043	0.2497	0.0010
shape	0.0324	0.0751	0.0006	0.5560	0.0009	0.0021	0.0002	0.0393	0.0293	0.0083
hardness	0.0008	0.0388	0.0031	0.1548	0.0004	0.0006	0.0011	0.0175	<.0001	<.0001
day*shape	0.7393	0.8421	0.4574	0.8443	0.7753	0.1889	0.1136	0.3322	0.9164	0.2009
day*hardness	0.9726	0.5969	0.9932	0.2430	0.8666	0.3310	0.6871	0.6669	0.0212	0.7109
shape*hardness	0.2603	0.6992	0.3046	0.7063	0.8320	0.5855	0.1666	0.2993	0.5339	0.8372
day*shape*hardness	0.8233	0.5302	0.8310	0.9620	0.5321	0.7491	0.1666	0.5504	0.5111	0.6040
day*gender	0.7393	0.1131	0.8041	0.1711	0.1554	0.4780	0.2718	0.3322	0.1174	0.2009
shape*gender	1.0000	0.5503	0.6794	0.3272	0.2549	0.4780	0.7134	0.4881	0.5999	0.4146
day*shape*gender	0.6178	0.5503	0.4574	0.5560	0.1554	0.4780	0.7134	0.3322	0.7528	0.9071
hardness*gender	0.7169	0.7569	0.7760	0.7629	0.1603	0.2815	0.9850	0.7779	0.5111	0.7109
day*hardness*gender	0.8948	0.9609	0.4153	0.3048	0.2910	0.8477	0.7295	0.7779	0.3606	0.3715
shape*hardness*gender	0.4743	0.4355	0.3046	0.7629	0.5321	0.9595	0.4266	0.8734	0.6649	0.8372
day*shape*hardness*gender	0.3416	0.4355	0.6499	0.3548	0.2290	0.5179	0.2509	0.1766	0.5339	0.2694

NOTE: Highlighting indicates significant findings ($p<0.05$)
Pr1, Pr2: Productivity, Eu1, Eu2: Ease of use, Fb1, Fb2: Feedback feel, El1, El2: Ease of learning, Sf1 Sf2: Satisfaction

Gender was not significant for any dependent measures except in interaction with shape for joined words. Females had more joined words when using keyboards with the circle key switch contact point whereas males had more joined words when using keyboard with square key switch contact point (Figure 6). With the exception of eu1[1], order was not significant for any dependent measure (Figure 7). Most dependent measures were significantly different across days but no significant day interaction effects were found except for an interaction of day and hardness for Sf1[2]. Since medium hardness was the best on both days for Sf1, the exception was a quantitative change but not qualitative (Figure 8). Therefore, all remaining analyses were conducted using data for both days. The details of day effects are described in the following section. To determine contribution of significant factor levels, Tukey HSD tests were performed, and mean scores and significances ($p<0.05$) are listed in Appendix I.

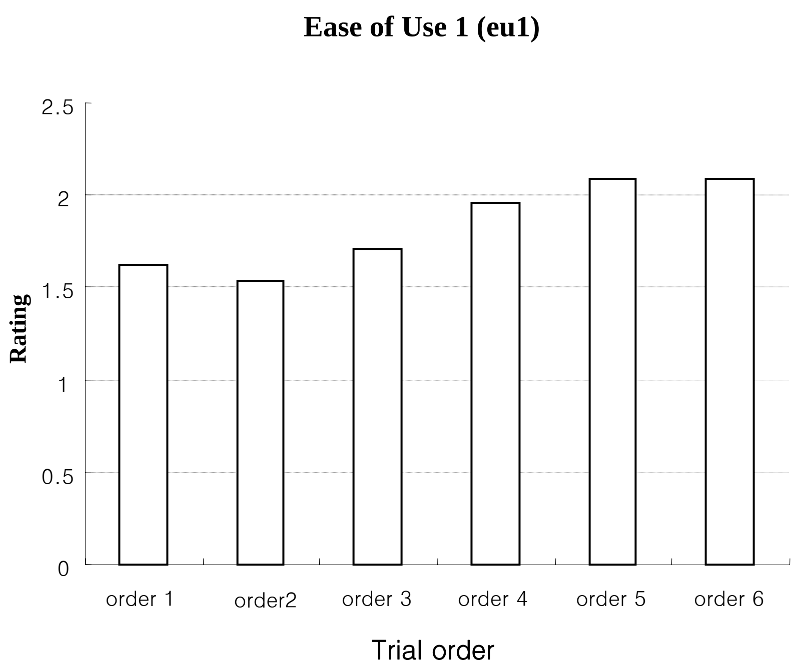
[1] Eu1 = I believe this flexible keyboard saves me typing time.
[2] Sf1 = My hand/fingers are comfortable when using this flexible keyboard.

Results



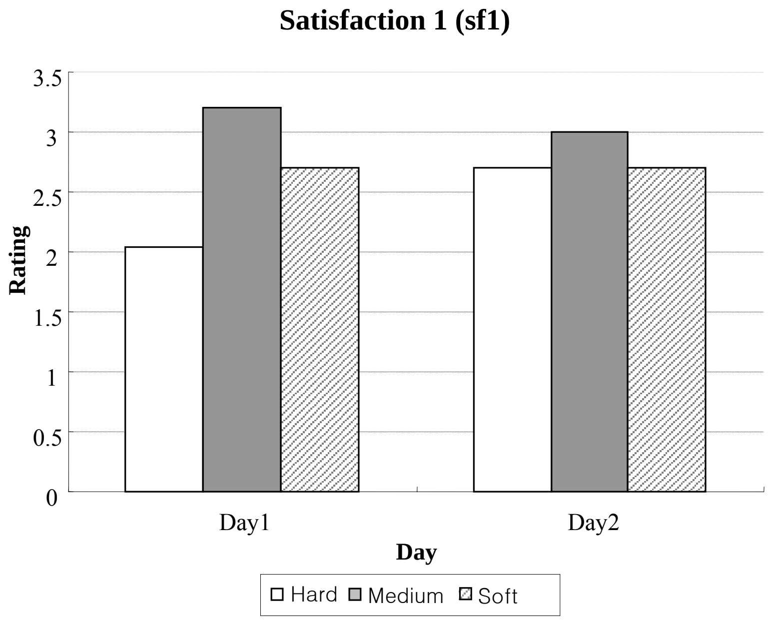
Level	Grouping		Mean
Male-Square	A		4.62
Female-Circle	A		3.92
Female-Square		B	1.97
Male-Circle		B	1.83

Figure 6. Results and groupings for Tukey's HSD tests for the gender-shape interaction.



Level	Grouping		Mean
order 5	A		2.08
order 6	A		2.08
order 4	A	B	1.96
order 3	A	B	1.71
order 1	A	B	1.63
order 2		B	1.54

Figure 7. Results and groupings for Tukey's HSD tests for the order effect on eu1 ratings.



Level	Grouping		Mean
Day 1-Medium	A		3.21
Day 2-Medium	A		3.00
Day 1-Soft	A		2.71
Day 2-Hard	A		2.71
Day 2-Soft	A		2.71
Day 1-Hard		B	2.04

Figure 8. Results and groupings for Tukey’s HSD tests for the day-shape interaction effect for Sf1 ratings.

Objective Measures

Day effects

The day effect was significant for net typing speed (NTS; $p< 0.002$), errors (ERR; $p< 0.0001$), missing words (MW; $p< 0.02$), misspelled words (MSW; $p< 0.0001$), and split words (SW; $p< 0.004$). NTS was significantly higher on day 2 (Figure 9), and ERR, MW, MSW, and SW were significantly lower on day 2 (Figures 10, and 11). However, it should be noted that no change was found in GTS, as NTS increased and ERR decreased on the second day. Misspelled words were the most common error type (Figure 11). These results indicate that participants’ typing accuracy improved over the two tests sessions, specifically by reducing misspelled words though GTS was unchanged.

Results

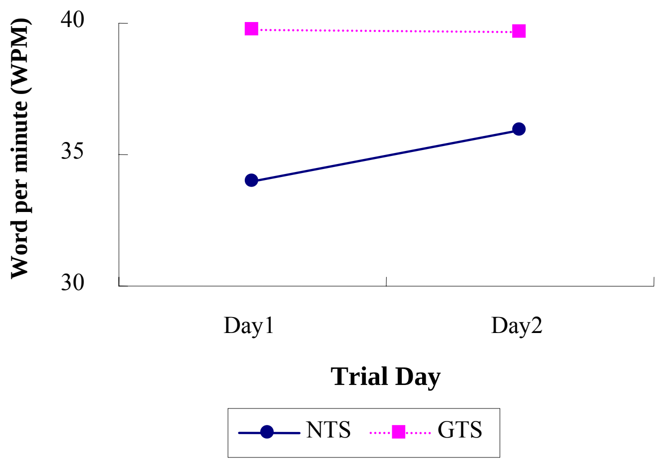


Figure 9. Average GTS and NTS by day.

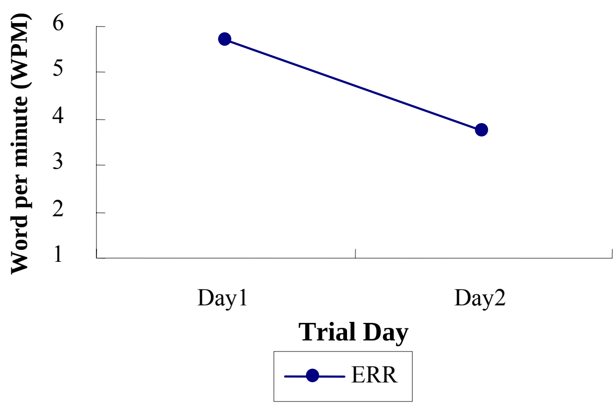


Figure 10. Average ERR by day.

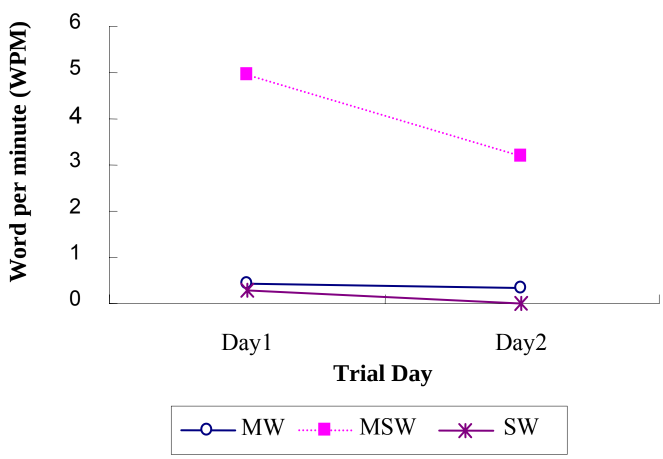


Figure 11. Average scores of ERR components by day.

Contact-point shape effects

Contact point shape was significant for NTS ($p<0.0001$), GTS ($p<0.02$), ERR ($p<0.02$), and MSW ($p<0.02$). Mean values of NTS and GTS for the square shape were significantly higher the square shape than for the circle shape (Figure 12). Also, ERR and MSW for the square shape were significantly lower than for the circle shape (Figure 13), while MS, EW, JW and SW were not affected by shape.

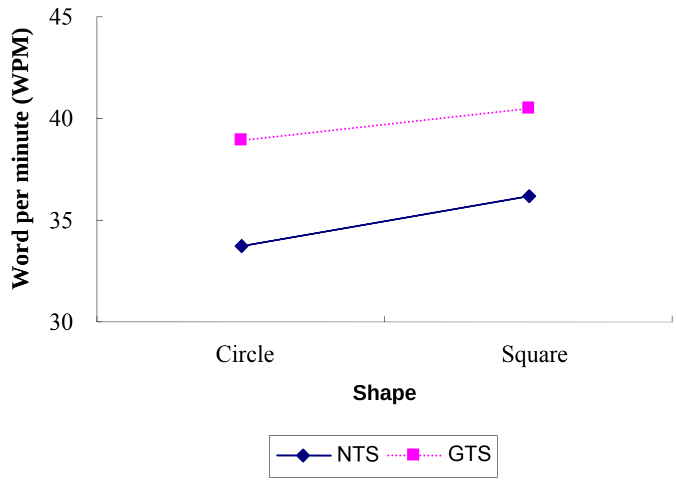


Figure 12. Average GTS and NTS by shape.

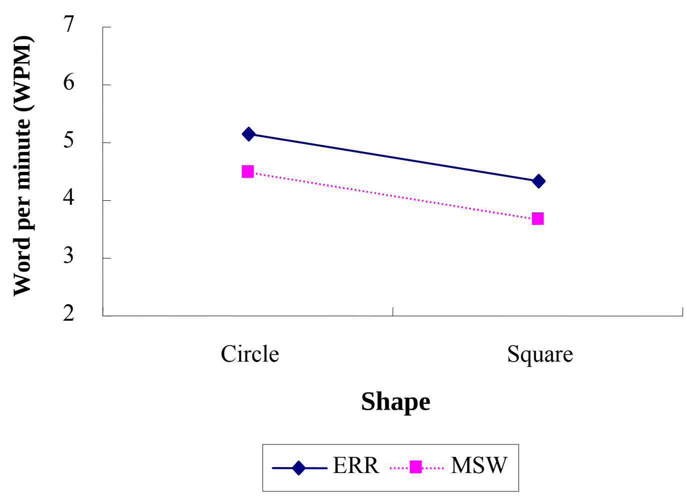


Figure 13. Average scores of ERR and MSW by shapes.

Material hardness effects

Material hardness significantly affected NTS ($p < 0.0001$), GTS ($p < 0.0004$), MW ($p < 0.0006$) and JW ($p < 0.0004$). Post-hoc comparisons indicated that mean values at the medium and soft levels were significantly higher than those at the hard level for NTS and GTS (Figure 14, Appendix I). MW and JW were significantly higher for the 'hard' hardness than 'soft' and 'medium' hardness. However, the mean value of MW and JW was so small that they did not seem to affect the number of errors (Figure 15). A detailed post-hoc comparison table for hardness is listed in Appendix I.

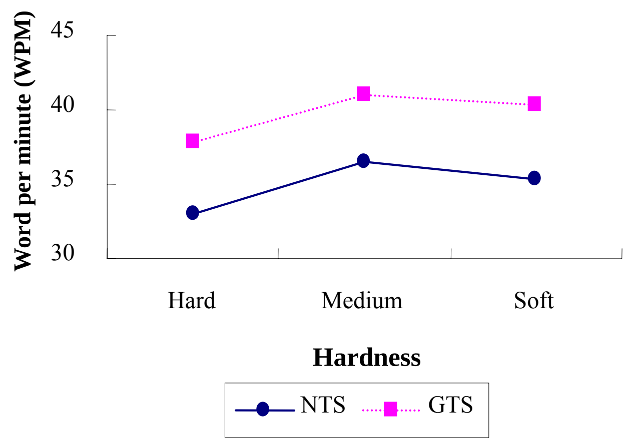


Figure 14. Average scores of GTS and NTS by hardness.

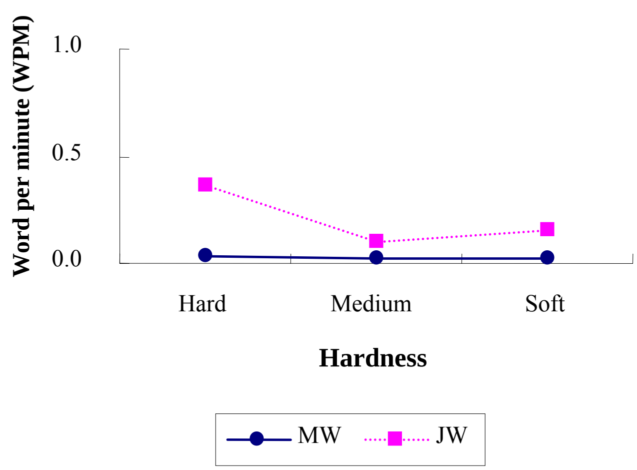


Figure 15. Average scores of MW and JW by hardness.

Shape and hardness interaction effects

An interaction effect between contact point shape and material hardness was found for NTS ($p < 0.004$) and GTS ($p < 0.006$). The six different combinations of keyboards are listed in Table 11.

Table 11. Types of Keyboard prototypes.

	Soft	Medium	Hard
Circle	K1	K3	K5
Square	K2	K4	K6

Post-hoc comparison indicated that mean values of NTS and GTS at K4 (combination of medium hardness and square shape) were significantly higher than other keyboards with mean (*SD*) values of 38.32 (7.99) and 42.39 (9.38) words per minute, respectively (Figures 16, and 17). Mean values of NTS and GTS at K1 (combination of hard hardness and circle shape) were significantly lower than other keyboards, with the mean (*SD*) values of 30.88 (5.31) and 36.04 (7.88) words per minute, respectively (Figures 16, and 17).

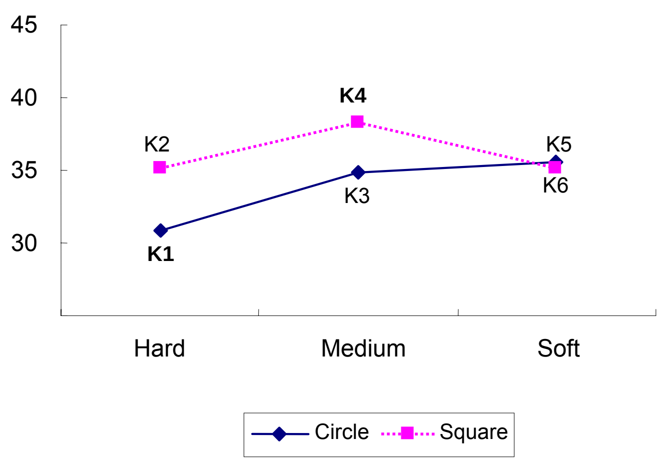


Figure 16. Interaction effect of hardness and shape on NTS.

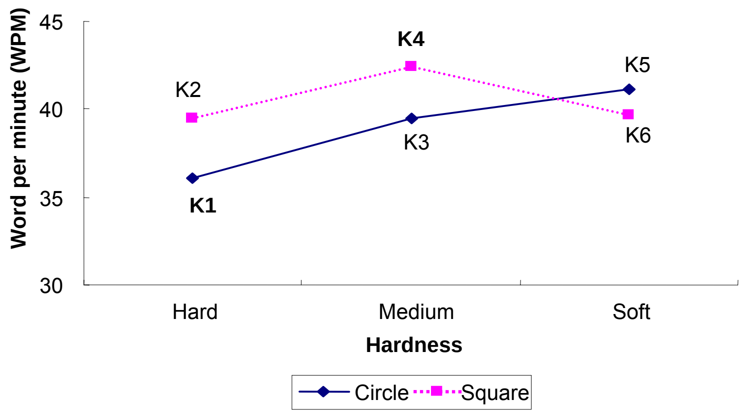


Figure 17. Interaction effect of hardness and shape on GTS.

Major findings for the objective measures were: (1) NTS was significant by day, shape, hardness, and interaction of shape and hardness, (2) GTS was significant by shape, hardness, and interaction of shape and hardness, (3) ERR was significant by day and shape, and (4) with the exception for EW, all error components (MW, MSW, JW, and SW) were affected by day, shape, hardness or interaction of shape and hardness, however, most errors were caused by MSW (Table 12).

Table 12. The number (ratio) of errors by error types.

Error type	MW	MSW	EW	JW	SW	Total ERR
Number (%)	5.76 (8.12%)	61.16 (86.21%)	0.54 (0.76%)	3.08 (4.34%)	0.41 (0.58%)	70.95 (100%)

Subjective measures

Day effects

A day effect was significant in four categories: productivity, ease of use, ease of learning, and satisfaction. All rating scores on day 2 were significantly higher than day 1, and pr1 (p<0.04), pr2 (p<0.0002), eu1 (p<0.0004), eu2 (p<0.002), el1 (p<0.003), el2 (p<0.005), and sf2 (p<0.002) were significant (Figure 18). However, fb1, fb2 and sf1 were not affected by day. All average (*SD*) rating scores are listed in Appendix G.

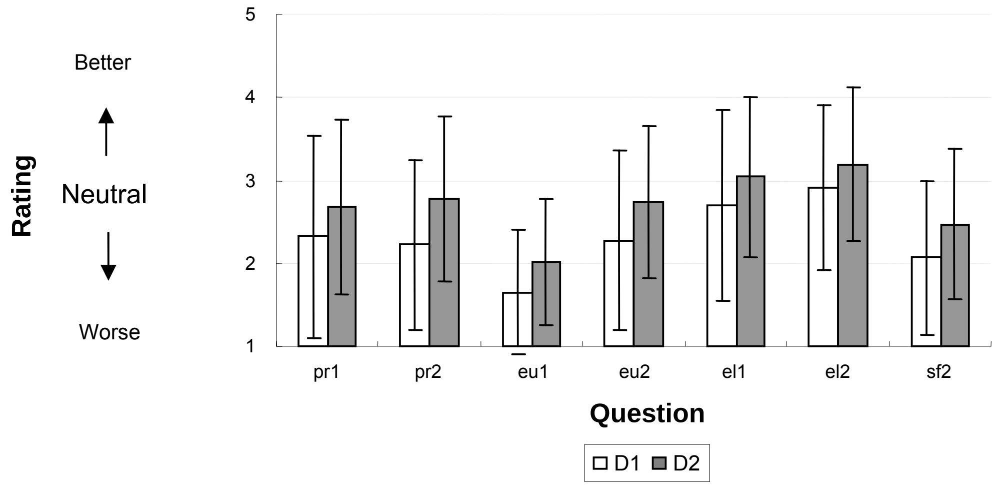


Figure 18. Average rating scores by day.

Contact-point shape effects

Contact point shape significantly effected ratings for pr1 (p<0.04), fb1 (p<0.0007), eu1 (p<0.001), eu2 (p<0.003), el1 (p<0.0003), el2 (p<0.04), sf1 (p<0.03) and sf2 (p<0.009). All the mean values of the square shape were significantly higher than the circle shape (Figure 19). Rating scores of pr2, fb2 and sf1 were not significantly affected shape. Although most rating scores were lower than 3 (Neutral), ratings of fb1 and el1 were around neutral.

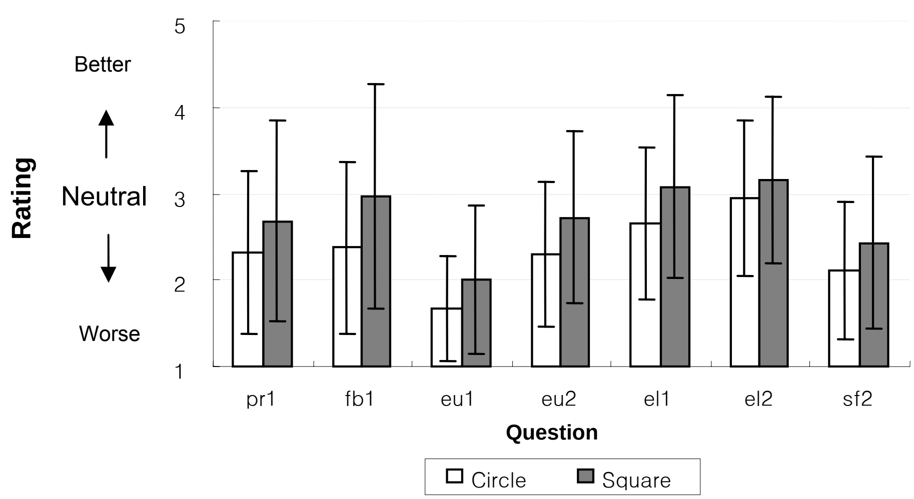


Figure 19. Average rating scores by contact-point shape.

Material hardness effect

Material hardness significantly effected ratings for pr1 (p<0.0009), pr2 (p<0.04), fb1 (p<0.004), eu1 (p<0.0005), eu2 (p<0.0007), el1 (p<<0.002), el2 (p<0.02), sf1 (p<0.0001) and sf2 (p<0.0001). The highest mean values were found for medium hardness, and the lowest mean values were found for hard hardness for all significant measures (Figure 20).

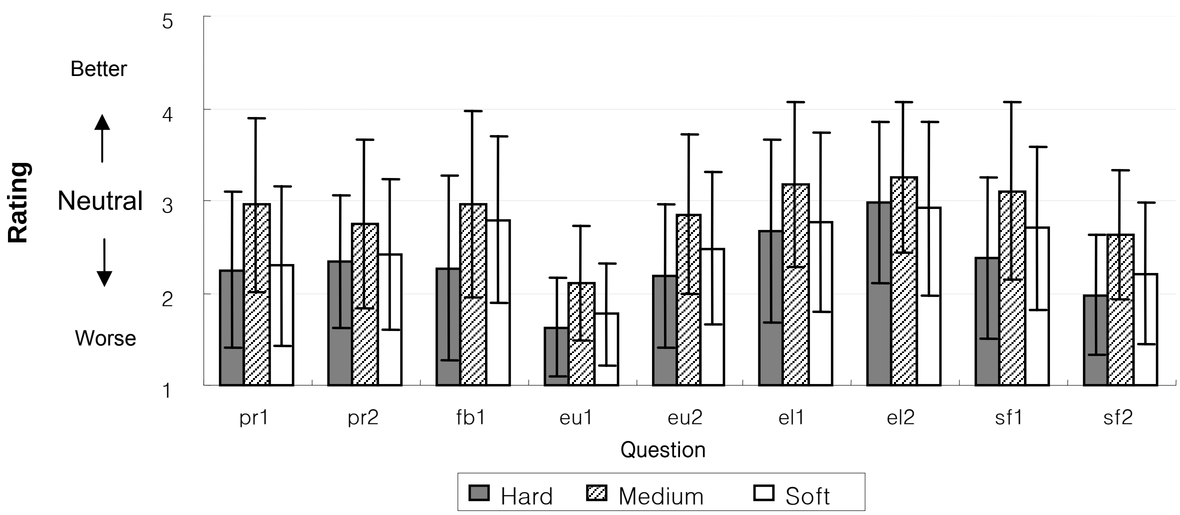


Figure 20. Average rating scores by material hardness.

Shape and hardness interaction effects

No significant effects were found for the shape and hardness interaction on usability ratings. However, for overall rating scores, similar trends were found here as the objective finding (NTS and GTS), the highest rating score was found for the K4 and the lowest was found for the K1 with the mean (*SD*) values of 2.16 (0.91) and 3.07 (0.89) respectively (Figure 21).

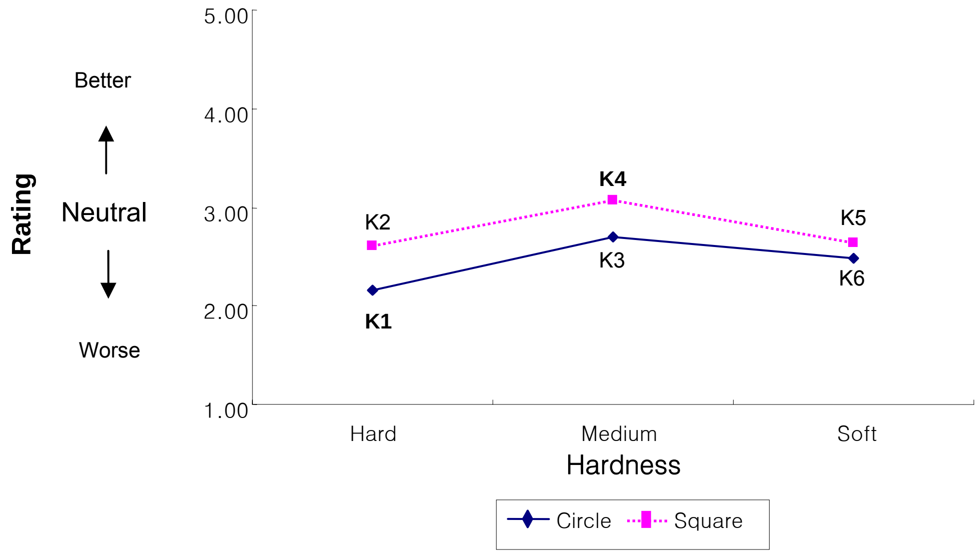


Figure 21. Interaction effect of hardness and shape on overall average rating scores.

In general, both objective and subjective scores increased across days, and most dependent measures were significantly affected by the main independent variables (contact point shape, material hardness). Subjective measure results had similar trends as the objective measure results (Figures 22, and 23). With the exception of fb2, the highest rating scores were found at K4, and the lowest scores were found at K1 for all questions. The overall mean (*SD*) of the subjective measures was 3.07 (0.89) at K4, and 2.16 (0.91) at K1 where 1 is the lowest, 3 is neutral, 5 is the highest rating number on the questionnaire.

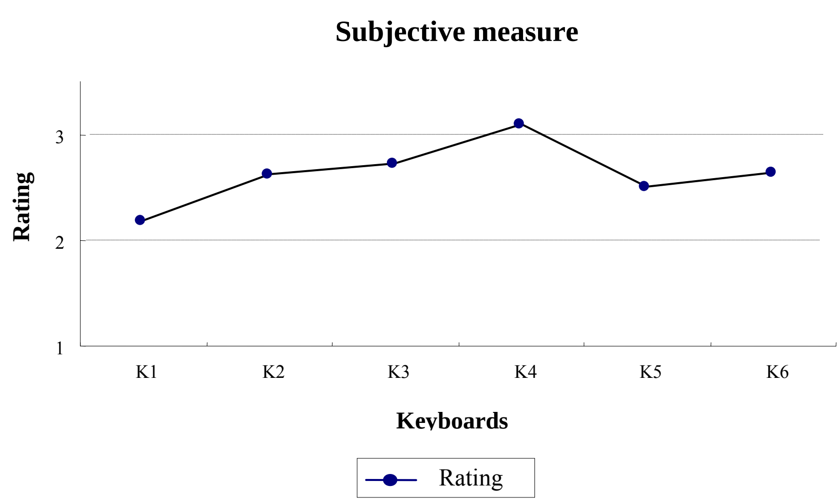


Figure 22. Overall rating scores of each keyboard.

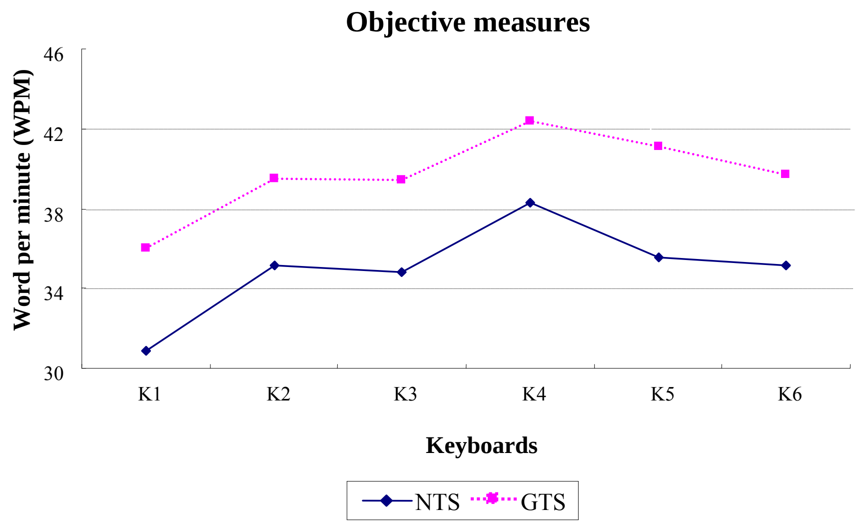


Figure 23. Average scores of each keyboard (NTS and GTS).

Exit Questionnaire

Participants rated the best flexible keyboard based on their previous trials. Mean (*SD*) rating scores for productivity (pr), feedback feel (fb), easy of use (eu) and easy of learning (el) were about the same or lower than neutral, and were 2.54 (0.81), 2.89 (0.91), 3.08 (0.78), 3.21 (0.76), and 2.37 (0.74), respectively. However, mean (*SD*) rating scores for mobility (mb) and design (de) were much higher than neutral, and were 4.33 (0.77) and 3.96 (0.63), respectively (Figure 24). Figure 25 shows mean (*SD*) values of individual questions.

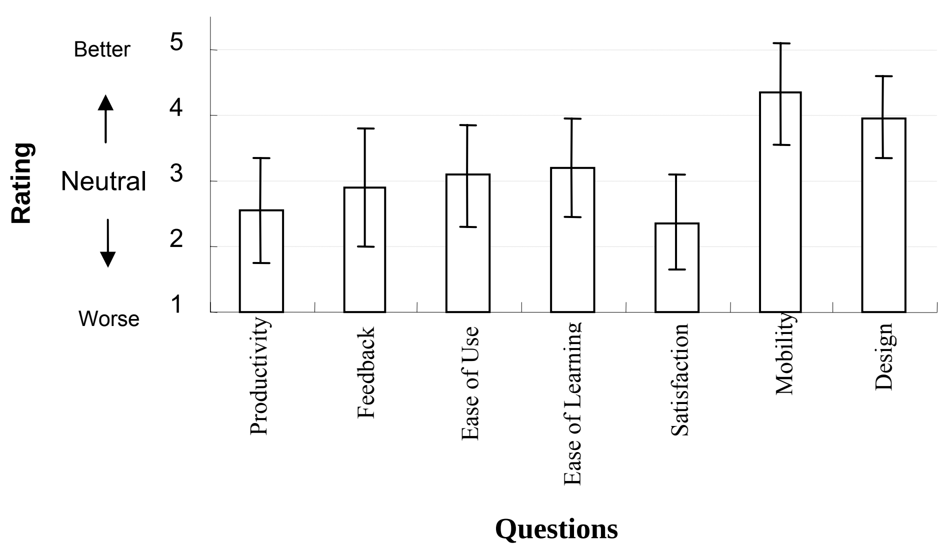


Figure 24. Overall rating scores of exit questions.

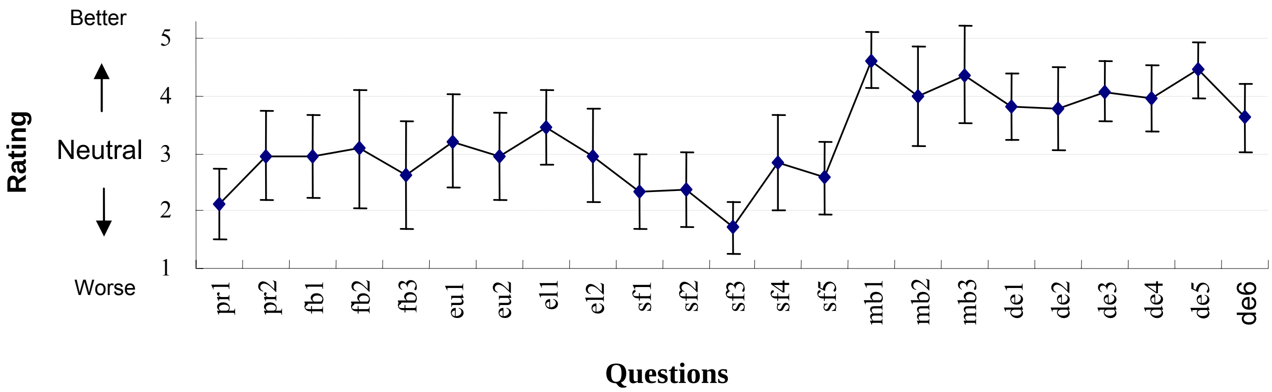


Figure 25. Average rating scores of exit questions.

In order to assess if participants could perceive differences in hardness among keyboards, they were asked to sort keyboards by hardness. Random probability of correctly assigning the keyboards was 33.3% (16 out of 48). Participants correctly assigned 52% to 54% of keyboards to a corresponding category, while 46% to 48% of keyboards were incorrectly assigned to the other two categories (Table 13). Participant seemed somewhat aware the differences in hardness, but the differences were not clear enough to distinguish correctly.

Table 13. Numbers and (%) of selected keyboards for hardness categories

Keyboards	K1, K2 (Hard)	K3, K4 (Medium)	K5, K6 (Soft)
Hard	26 (54%)	11 (23%)	11 (23%)
Medium	11 (23%)	25 (52%)	12 (25%)
Soft	11 (23%)	12 (25%)	25 (52%)

Correlation

All variables had samples of $N = 144$, thus critical values are $|r| \geq 0.254$ (Fisher, 1973) for Pearson's correlations for $df = 142$ and $p < 0.01$. Correlation tables and partial scatter plots for both objective and subjective measures are listed in subsequent sections, and complete scatter plot and linear correlation tables (including *p* values) are available in Appendix J and K respectively.

Objective measures

All measures of typing performances were positively correlated each other (Table 14). NTS was strongly correlated with GTS (r = 0.928), SW(r = 0.427), and EW(r = 0.357). Overall ERR increased as GTS increased (r = 0.623). ERR were strongly correlated with MSW (r = 0.983), MW(r = 0.617), JW (r = 0.462), and EW(r = 0.398). MW was strongly correlated with JW (r = 0.826) and MSW (r = 0.473). MSW and EW were correlated with EW (r = 0.396) and SW (r = 0.454), respectively. As seen in the scatter plot (Figure 26), NTS was strongly correlated with GTS but not with ERR and MSW. GTS was strongly correlated with ERR and MSW, which also strongly correlated with ERR (Figure 27).

Table 14. Correlation r-values of objective measures

	NTS	GTS	ERR	MW	MSW	EW	JW	SW
NTS	1.0000	0.9276	0.2850	0.0461	0.2799	0.3574	0.1473	0.4274
GTS		1.0000	0.6225	0.2780	0.6115	0.4467	0.3005	0.4331
ERR			1.0000	0.6168	0.9825	0.3975	0.4624	0.2158
MW				1.0000	0.4727	0.1168	0.8262	0.0175
MSW					1.0000	0.3959	0.2985	0.2082
EW						1.0000	0.0608	0.4540
JW							1.0000	0.0089
SW								1.0000

The highlighted indicate significant correlation. (p<0.01)

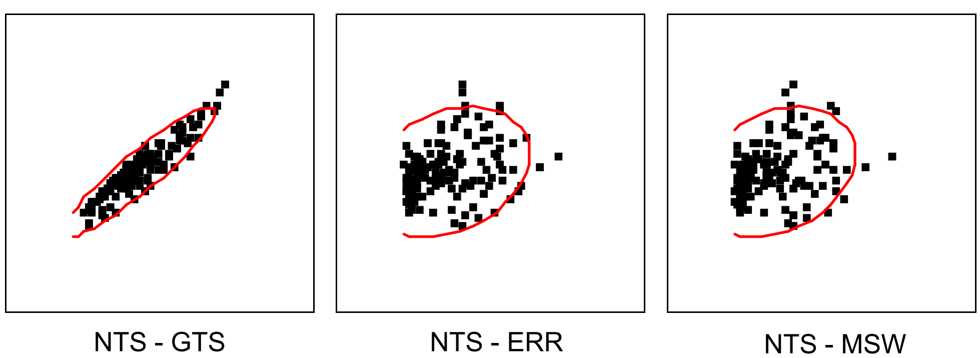


Figure 26. Correlations between NTS and GTS, ERR and MSW

Figure 27. Correlations between GTS, ERR, and MSW

Subjective measures

All subjective measures were positively correlated with each other (Table 15). Overall, strong correlations were found between all subjective measures except for Fb2. Fb2 was not significantly correlated with any other subjective measure (*r* values from 0.007 to 0.186). With an exception of the correlation between fb1 and fb2 (*r* = 0.064), all pairs of questions within the same categories showed strong correlation with each other (*r* values from 0.631 to 0.813). In addition, all categories also strongly correlated with each other (*r* values from 0.467 to 0.810) except the feedback category. Following scatter plots illustrate correlations between two questions which within the same or similar categories (Figures 28, and 29).

Table 15. Correlation r-values of subjective measures

	pr1	**pr2**	**fb1**	**fb2**	**eu1**	**eu2**	**el1**	**el2**	**sf1**	**sf2**
pr1	1.0000	0.8132	0.3285	0.0854	0.6493	0.7032	0.6137	0.5283	0.6164	0.8097
pr2		1.0000	0.3244	0.1741	0.6130	0.6657	0.5400	0.4795	0.6803	0.7644
fb1			1.0000	0.0639	0.4491	0.4022	0.2432	0.1660	0.4551	0.4379
fb2				1.0000	0.1397	0.1002	0.0072	0.0786	0.1856	0.1165
eu1					1.0000	0.6312	0.5955	0.4662	0.5853	0.7105
eu2						1.0000	0.7123	0.6602	0.6544	0.7070
el1							1.0000	0.8125	0.6004	0.6021
el2								1.0000	0.4961	0.5184
sf1									1.0000	0.7218
sf2										1.0000

The highlighted indicate significant correlation. (p<0.01)

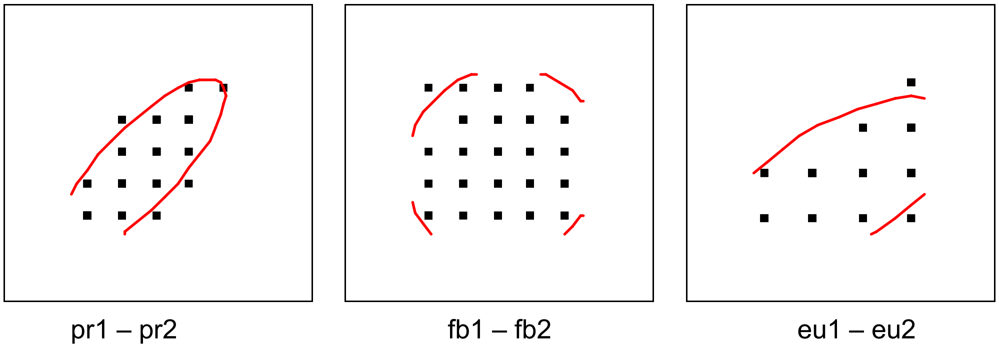


Figure 28. Correlations between pr1-pr2, fb1-fb2, and eu1-eu2

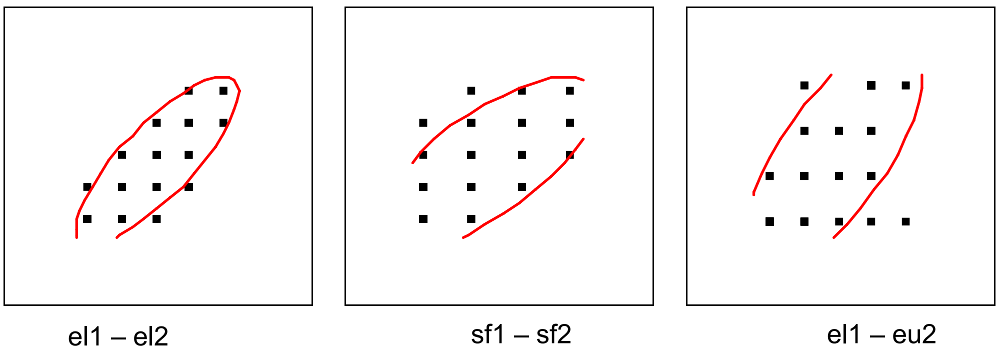


Figure 29. Correlations between el1-el2, sf1-sf2, and el1-el2

Objective vs. Subjective measures

All subjective measures were positively correlated with NTS and GTS (*r* values from 0.121 to 0.309) except for fb2 (*r* = -0.252, and -0.294). Significant correlations were found between NTS and GTS and several subjective measures (Figures 30 and 31). ERR and error types were negatively correlated with most subjective measures but the correlations were very weak. Correlation *r*-values between objective and subjective measures are listed in Table 16.

Table 16. Correlation r-values between objective and subjective measures

	pr1	pr2	fb1	fb2	eu1	eu2	el1	el2	sf1	sf2
NTS	0.3088	0.2536	0.1623	-0.2520	0.2368	0.2629	0.2038	0.2258	0.2086	0.3102
GTS	0.2692	0.2041	0.1359	-0.2936	0.1486	0.1812	0.1218	0.1478	0.2457	0.2625
ERR	0.0439	-0.0076	0.0087	-0.2255	-0.1146	-0.0858	-0.1144	-0.0940	0.1934	0.0239
MW	-0.0971	-0.1060	-0.1491	-0.2340	-0.2201	-0.1020	-0.1130	-0.1138	-0.0006	-0.1298
MSW	0.0749	0.0152	0.0487	-0.1917	-0.0789	-0.0703	-0.0960	-0.0741	0.2261	0.0560
EW	-0.0261	-0.0144	0.0457	-0.0483	0.0775	0.0252	-0.0190	0.0171	0.0210	0.0312
JW	-0.1092	-0.0726	-0.1653	-0.2556	-0.1804	-0.1041	-0.1211	-0.1353	-0.0551	-0.1190
SW	-0.0200	-0.1105	-0.1006	-0.0857	-0.1630	-0.0826	-0.1796	-0.0806	-0.1064	-0.0069

The highlighted indicate significant correlation. (p<0.01)

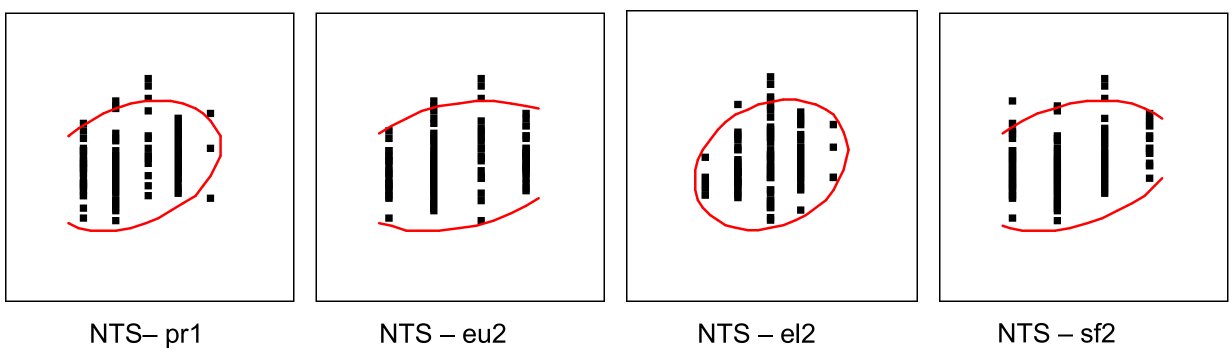


Figure 30. Correlations between NTS and pr1, eu2, el1, and sf2.

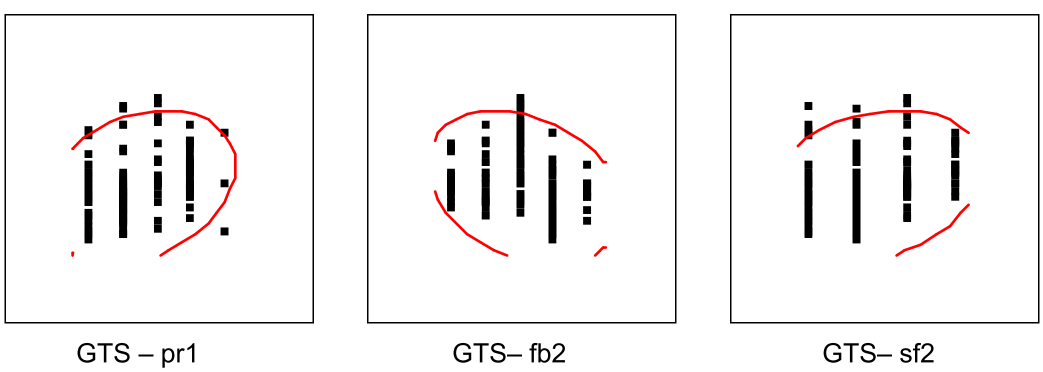


Figure 31. Correlations between GTS and pr1, eu2, fb2, and sf2.

Categorical analysis (Objective vs. Subjective)

To verify the correlations between objectives and subjective measure, a categorical analysis was performed in which NTS (a representative of objective measures) and all rating scores of each participant were compared for contact point shape and material hardness. Table 17 shows the results of the analysis by the contact point shape, and Table 18 shows the material hardness results. In the matrix for Pr1, for instance, if a participant who showed a higher NTS with the circle shaped contact point than with the square, and rated the circle with a higher score, he/she was assigned to the upper left corner of the matrix. Conversely, if a person rated the square shape higher than the circle although he/she achieved the higher NTS with the circle, the participant was counted in the lower left corner. If the same rating was found at the circle and square shape, then it was tallied at both upper and lower left corner. Therefore, the number of participants for each matrix may exceed the actual number of participants (N =12).

Diagonal ellipses in Table 17 and 18 indicate the number of participants whose objective results concur with their subjective ratings. Bold numbers in Table 18 indicate the number of participants who rated the highest score at medium or soft and also made highest NTS score using medium or soft hardness keyboards. The complete categorical compression matrices of NTS by all subjective measures for shape and hardness are listed in Tables 17, and 18, respectively.

Table 17. NTS by Subjective measures for Shape

	Pr1		**Pr2**		**Fb1**		**Fb2**		**Eu1**	
	Circle	Square	Circle	Square	Circle	Square	Circle	Square	Circle	Square
Circle	1	1	2	0	1	1	2	8	1	1
Square	1	9	2	9	2	10	10	6	1	9

	Eu2		**El1**		**El2**		**Sf1**		**Sf2**	
	Circle	Square	Circle	Square	Circle	Square	Circle	Square	Circle	Square
Circle	1	1	1	1	2	0	1	1	1	1
Square	1	9	1	9	3	9	2	10	2	10

Table 18. NTS by Subjective measures for Hardness

	Pr1 H	Pr1 M	Pr1 S	Pr2 H	Pr2 M	Pr2 S	Fb1 H	Fb1 M	Fb1 S	Fb2 H	Fb2 M	Fb2 S	Eu1 H	Eu1 M	Eu1 S
Hard	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium	1	**7**	**2**	1	**7**	**3**	1	**7**	**5**	7	**6**	**7**	1	**8**	**2**
Soft	0	**3**	**0**	0	**2**	**1**	0	**2**	**6**	1	**1**	**3**	1	**3**	**1**

	Eu2 H	Eu2 M	Eu2 S	El1 H	El1 M	El1 S	El2 H	El2 M	El2 S	Sf1 H	Sf1 M	Sf1 S	Sf2 H	Sf2 M	Sf2 S
Hard	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium	0	**7**	**3**	3	**7**	**3**	3	**8**	**5**	1	**7**	**5**	1	**8**	**2**
Soft	0	**2**	**1**	1	**2**	**1**	0	**3**	**1**	0	**3**	**0**	0	**3**	**0**

The results of categorical correlation matrices for shape support that NTS was strongly and positively correlated with most of subjective measures, while fb2 showed weak and negative correlation. For instance, participants whose rating results concurred with higher NTS for pr1, pr 2, eu1, eu2, and el 1, for shapes were 10 out of 12 (83.3 %). On the other hand, participants whose rating results did not concur with higher NTS for shapes fb2 were 69.2 % (18 out of 26). These ratios implied that NTS was correlated strong and positively with pr1, and was moderate and negatively correlated with fb2 for shape.

With the same procedure, the categorical correlation matrices for hardness revealed that NTS and subjective measures seemed not well correlated with each other. However, according to the Tukey test of NTS for hardness, medium and soft hardness were not significant each other, while hard hardness was significant from both medium and soft hardness (Appendix I). Therefore, even the categorical matrices of medium and soft hardness were not precisely agreed with each other, the results of both NTS and subjective measures show that medium hardness was the best, soft hardness was the second, and hard hardness was the worst which are the similar result to objective measures.

DISCUSSION

The goals of this research focused on identifying the effect of two characteristics of flexible keyboards, keyboard material hardness and key switch-contact point shape. Overall, the square shaped key-switch contact point led to better typing performance than circle shaped contact points. Regarding material hardness, medium and soft material hardness led to better typing performance than hard hardness. A combination of square shape and medium hardness showed the best performance, and a combination of circle shape and hard hardness showed worst performance, among the six different keyboards.

For the subjective measures, the results of the usability ratings revealed user satisfaction trends of the keyboards were in accordance with the result of objective measures. Overall, square shaped key-switch contact point keyboards received better rating scores than circle shaped contact point keyboards. Among the three different harnesses, medium hardness keyboards received highest ratings, hard hardness received the lowest ratings of material, and soft hardness keyboards were rated between medium and hard hardness keyboards. Although no significant differences were found for the interaction between the shape and hardness, the usability rating trends were similar to the objective measure results. Highest ratings were found for K4 and the lowest ratings were found for K1.

Gender and order did not significantly affect the dependent variables. However, most dependent measures were significantly influenced by day. All the significant dependent measures showed better performance on day2, perhaps caused by learning effects.

Day

NTS was increased and ERR were decreased from day 1 to day 2, but GTS was unchanged across days. This implies that the reason for increased NTS was not caused by an increase in typing speed overall change of GTS but a reduction in the number of errors. With the exception of EW, all error types (MW, MSW, JW, and SW) were decreased on day 2, and thus the participant performed better. Ratings on some questions (pr2, eu1, el2 and sf2) were significant across days and all mean usability ratings were higher on day2. There was day effect for both subjective and objective measures but no significant day interaction effects were found except for an interaction of day by hardness for sf1. This result might imply that if participants used the keyboards for longer time periods, they may be able to fully adapt to typing flexible keyboards and learn how to type efficiently and at a level equivalent to standard keyboards.

Contact-point shape

NTS and GTS were increased and ERR were decreased when using square shaped contact point keyboards. Specifically, MSW was significant, but shapes did not affect the other error components. The contact point shape affects pr1, fb1, eu1, eu2, el1, sf1 and sf2. With the exception of fb2, all mean scores of usability rating were higher for the square shape. A previous study provides conflicting results in effect of switch contact point shape. Ohtsuka et al. (1998) examined the effects of mechanical switch contact points shape on contact resistance. They found that the different characteristics of contact points (16 mm circular shape and 9mm hemispheric shape) were almost equal to each other, and there was no significant difference between the contact point characteristics. However, unlike the standard mechanical key switch, flexible keyboard switch has lateral movement and, thus, the contact region may not be consistent. As mentioned earlier, lateral key movement may reduce the key travel distance and may the cause of switch closing errors. The square (9 mm) switch-contact point was assumed to extend the contact region of the key switch-contact point compensate for lateral and reduced key travel distance. Potentially, the findings of this study support the initial assumption. Therefore, it can be concluded that shape of key switch-contact point might be a critical factor that affects both typing performance and usability of flexible keyboard.

Material hardness

NTS and GTS were increased when using medium or soft hardness keyboards compared to using hard hardness keyboards. ERR were not significant for hardness of the keyboards, but MS and JW were significantly increased for hard hardness. However, due to the small contribution to the total number of errors, MS and JW do not significantly affect overall error rates (Table 12). Therefore, the increased NTS was not produced by a reduced ERR but increased GTS. Potentially, the different hardness levels require different activation forces, with hard hardness keyboards requiring more key activation force leading to increases in MW and JW due to switch-closing error. With an the exception of fb2, all usability ratings for medium hardness were higher than soft and hard, while fb2 was not affected by material hardness.

Regarding tactile and auditory feedback (fb1and fb2, respectively), findings were contradictory to those found for standard keyboard designs. The findings in this study did not support results found by Yoshtake et al. (1997) that found that keyboards with unclear tactile and auditory feedback tended to result in higher error rates than keyboards with clear tactile and auditory feedback. With regard to preference, participants were divided into two groups: those who preferred an unclear tactile feedback with no clicking sound, and those who preferred a clear tactile feedback with clicking sound. However, the current study showed that tactile (fb1) and auditory feedback (fb2) were not correlated with error rate as well as any variables of typing performance except GTS for fb2. In addition, user preference for fb2 was not significantly different for material hardness, which produces tactile feedback. However, this conflicting result may be the result of participants being unable to distinguish differences in tactile and auditory feedback among the six different flexible keyboards, as evidenced by they exit questionnaire results.

The findings in this study support results found by Gerard et al. (1999) that key-switch stiffness effects subjective discomfort level. They found subjective discomfort was significantly higher for stiff key-switch designs, and most participants preferred the medium stiffness keyboard. The results of previous studies reveal that tactile feedback, auditory feedback, key-switch stiffness affect user preference and typing performance. However, flexible keyboard may produce similar tactile and auditory feedback along with different hardness.

Shape and hardness Interaction

NTS, GTS, and JW were significantly affected by the interaction between contact point shape and material hardness. ERR were not affected by the interaction, but JW were significant. For an interaction between medium or soft hardness and square shape, mean values of NTS and GTS were significantly higher, and JW were significantly lower than other configurations. Meanwhile, an interaction between hard hardness and circle shape resulted in significantly lower NTS and GTS, and significantly higher JW than other configurations. Unsurprisingly, a combination of better factor levels (square shape and medium hardness) yielded better results than a combination of worse factor levels yield worse result likewise. In addition, although no significant differences were found for usability ratings, the trends of interaction effects were similar to the objective measure findings.

Correlation

All objective measures were positively correlated each other, and all subjective measures were positively correlated with each other. With the exception of NTS and GTS with several subjective measures, correlations between objective and subjective measure were not strong, and ERR and types of errors were negatively correlated with most subjective measures. However, the results of categorical matrices reveal that there was a possibility to obtain similar results of the objective analysis through the results subjective analysis or vice-versa.

Exit question

When participants responded the exit questionnaire, they were asked to imagine the “best” flexible keyboard based on their previous trials. Overall, mean (SD) score of usability questions of the flexible keyboards were about the same or slightly lower than neutral and were from 2.37 (0.47) to 3.21 (0.66). However, mean (SD) scores for mobility and design were much higher than neutral and were 4.33 (0.59) and 3.96 (0.36), respectively.

CONCLUSION

Limitations

This study was limited to only two factors (shape of contact point and material hardness) with only two and three levels, respectively. In this study, the square shape and medium hardness and their combination showed best performance among the other combinations. However, more factor levels may be available, such as other shapes and hardness. Further, size of the shapes, which may affect typing performance, was not considered.

Although several error components were available to measure, it was not specific enough to determine if the errors were caused by human error or mechanical failure. Another limitation is inability of recording other aspects of typing performance. For example, if participants made errors and corrected the errors during task performance, the corrected errors were not counted in the number of errors but spent time resulting in reduced GTS. If all aspects of typing performance had been recorded, it may have been possible to determine specific reasons for the errors. For instance, if a participant typed “tyoing” instead of “typing”, it can be considered as human error because “o” and “p” is a different key. On the other hand, if a participant type “ttyping” or “tpng”, it might be a mechanical failure caused by double closing or unclosing the key switch.

Participants in this study were restricted in net typing speed (36-57 words per minute), and almost all of them were college students in the same age group. This group may not represent all potential user groups.

Future Directions

As mentioned above, this study examined only two physical factors among many physical, psychosocial, and individual factors that could be contribute to typing performance and usability aspects. The impact of factors (e.g. size of the contact point, contact surface, key skirt design, and circuit board design) could be studied to improve flexible keyboard performance. In this study, only certain aspects of usability were examined using self-rating questionnaires. Future studies should examine additional usability questions (e.g. why and what they like or do not like the flexible keyboard, level of comfortable, mobility and application, etc) to assess potential design modifications to promote a user-friendly product.

Future research could examine various types of flexible keyboards in the market. It may provide more opportunity to find critical characteristics of flexible keyboard designs on performance and usability. Since several types of flexible keyboards are currently available, examination of the various types of keyboards may lead to find diverse design issues. Field studies could be considered to assess the effects of various working environments to on usability.

Contributions

Little or no previous research exists for flexible keyboards. Previous keyboard studies have focused on performance, design and usability of standard keyboards and other types of data-entry devices. This study investigated the impact of key-contact point shape and material hardness of the flexible keyboards, factors directly impact typing performance and usability.

This study provides evidence that both typing performance and usability of the flexible membrane keyboard are affected by the material hardness and the contact point shape. The medium or soft material hardness and square shape lead to better typing performance and usability. Overall, usability ratings for best flexible keyboard were reached to the neutral level, while mobility and design were much higher than neutral.

Finally, a recommendation can be established through current study for general design guideline of the flexible keyboards. Square shaped contact point leads to increase typing speed and decrease error rate, and medium or soft hardness lead to increase typing speed. Therefore, a combination between square shape and medium or soft hardness is recommended over other combinations. Surprisingly, the worst keyboard, a combination between circle shape and hard hardness, is the same one which is currently sold in the market place. In addition, potential finding is flexible keyboards may useful for small size laptop or hand-held device due to the mobility, water and dust resistance, and application.

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Appendix A: IRB Consent Form

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING (ISE)

Informed Consent for Participants of Investigative Projects

Title of Project: "A usability study of flexible membrane keyboards"

Principal Investigator: Maury A. Nussbaum, Ph. D., Associate Professor, ISE
Kari Babski-Reeves, Ph. D., Assistant Professor, ISE
Dong Jae Shin, Graduate Student, ISE

I. Purpose of This Study

You are invited to participate in a study to identify optimal interaction between two selected factors of flexible membrane keyboards. A controlled experimental design and subjective research will be conducted to obtain data for evaluating usability of the flexible membrane keyboards. The object of this research is making design suggestions to improve typing speed and reduce error rate of the flexible membrane computer keyboard.

II. Procedure

A total of 12 participants will be asked to read, sign and fill out on approved informed consent documents, demographic, musculoskeletal questionnaire and anthropometric data will also be collected. You will be required to complete a total of eight tests of typing tasks. A test will be 15-minute test session and take 5-minue breaks between each session. You will be asked to fill out subjective questionnaire during rest period. The same procedure will be repeated for each experimental condition until all eight tests have been completed. Exit question will be presented when you have finished the entire experimental conditions. Total testing session time is expected to last for 2 to 2.5 hours.

III. Risks and Benefits

There is no risk associated with this study that would not be found in daily office activities. Temporary discomfort or fatigue in the hands, wrists, and/or forearms may result due to the eight tests of typing tasks; however, you are encouraged to discontinue typing task if you experience extreme discomfort. You will be compensated for your participation, and you will be given information to contact the principal investigator to get information about the outcomes of the study. By participating in this study, you will be assisting the investigators in possibly identifying an ideal hardness and key switch-contact design of a soft, flexible membrane computer keyboard.

IV. Extent of Anonymity and Confidentiality

Your identity will be kept in the strictest of confidence. No names will appear on questionnaires or surveys, and a coding system will be used to associate your identity with questionnaire answers and data. All information will be collected in a file and locked when not being used. The list associating names with answers will be destroyed after one month of data collection. No videotaping or audiotaping will occur during the experiment.

V. Compensation

Compensation is offered for participating in this study, set at $7/hour, rounding to the quarter-hour if necessary.

VI. Freedom to Withdraw

You are free to withdraw from this study at any time for any reason without penalty. If you choose to withdraw during the study, you will be compensated for the portion of the testing which has been completed.

VII. Approval of Research

This research project has been approved, as required, by the Institutional Review Board for research involving human participants at Virginia Polytechnic Institute and State University, and by the Department of Industrial Engineering.

VIII. Participant's Responsibilities

I voluntarily agree to participate in this study. I have the following responsibilities:

- To read and understand the purpose of the study.
- To answer questions, surveys, etc. honestly and to the best of my ability
- To type as naturally and consistently as possible for each of the experimental conditions
- Be able to openly discuss (vocalize) any comforts or discomforts I experience during or in between typing tasks at the moment I experience them
- Be aware that I am free to ask questions at any point time
- To refrain from discussing any details of this experiment with others

IX. Participant's Permission

I have read and understand the Informed Consent and conditions of this research project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I reserve the right to withdraw at any time without penalty. I agree to abide by the rules of this project.

____ ____________________

Participant’s Signature Date

Signature Page

I have read a description of this study and understand the nature of the research and my rights as a participant. I hereby consent to participate, with the understanding that I may discontinue participation at any time if I choose to do so.

Signature ____

Printed Name ____

Date ____

The research team for this experiment includes Dr. Babski-Reeves, Dr. Maury A. Nussbaum, and Dong Jae Shin. Research team members may be contacted at the following information.

Grado Department of Industrial and Systems Engineering
250 Durham Hall
Blacksburg, VA 24061

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Graduate Student, Industrial and Systems Engineering
550 Whittemore Hall, Phone: (540) 231-5359, Email: djshin@vt.edu

In addition, if you have detailed questions regarding your rights as a participant in University research, you may contact the following individual:

Dr. David Moore
Chair, Institutional Review Board
CVM Phase II (Pathobiology)
Virginia Tech
Blacksburg, VA 24061
(540) 231-4991

Appendix B: Demographic Data Collection Form

Participant CODE:________________ Date ___/___/ 04 (mm/dd/yy)

Demographic Information

1. Age: ________

2. Gender: □ Female □ Male

3. Dominant hand: □ Left □ Right □ Both

4. Type with ten fingers? □ Yes □No

5. How long have you used a computer **keyboard**? ________Years ______months

6. How many hours do you typically use a computer **keyboard**? _____h/Day or ___h/Week

7. What type of **keyboard** do you use most often?

   □ Standard keyboard □ Laptop keyboard □ "Natural" or split key keyboard
   □ Other type of keyboard (please specify) ___________________

8. Did you know anything about "Flexible computer keyboards" before? □ Yes □No

9. Please specify if you chose "Yes":

   When_____________________
   Where_____________________
   Experience of use, if any: ____

Appendix C: Musculoskeletal Questionnaire

Musculoskeletal Questionnaire

Please answer the following questions, check on the box, where appropriate.

1. Have you had any trouble (ache, pain, discomfort) in wrists, hands or fingers at any time during the last 12 months or Today?

□No □Yes

If "yes", please circle on the picture.

L R

When:____________________

How long:_____________________

Please specify:____

Past Medical History

1. Fracture or break in wrist, hand or finger? L / R
   □No □Yes
   If "yes", please specify:____

2. Have you ever been diagnosed by a physician with arthritis of the wrist, hand, or fingers? L / R
   □No □Yes
   If "yes", please specify:____

3. Experience pain, numbness, or tingling in wrist, hands or fingers? L / R
   □No □Yes
   If "yes", please specify:____

4. Do you have any condition that limits your ability to move/bend your wrist, hand, or fingers? L / R
   □No □Yes
   If "yes", please specify:____

Appendix D: Post-task Questionnaire

Participant CODE:______________ Treatment condition CODE:_

Rate your opinion on a scale, as compared to the standard keyboard

Productivity I can effectively type using this flexible keyboard.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
The flexible keyboard is useful to type.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
Feedback feel The flexible keyboard requires a little amount of force to push the key.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
I prefer the reduced key-clicking (typing) sound.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
Ease of Use I believe this flexible keyboard saves me typing time.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
This flexible keyboard is easy to use.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
Ease of Learning I can easily accommodate to this flexible keyboard.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
It is easy to learn to use this flexible keyboard.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
Satisfaction My hand/fingers are comfortable when using this flexible keyboard.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
I am satisfied with the flexible keyboard	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree

Feel free to write any comments, if you have any:

Aenppendix E: Exit Questionnaire

Exit QuestionnaireI Participant CODE:___________

Exit Questions

1. Please try all of the keyboards and assign each key board into one of the following hardness categories.

Hard	
Medium	
Soft	

When answering the following questions, please think of "The Best Flexible-keyboard" you ranked the highest in the previous question.

2. If the functions and price were all the same, I would prefer;

□ Standard keyboard □ Laptop keyboard □ The best flexible keyboard

□ Other____

3. I would use the best flexible keyboard with (check all that apply);

□ Laptop Computer □Desktop Computer □PDA □Other_________________________

4. Give your opinion about an appropriate price for the best flexible keyboard.

* A market price of standard keyboards are approximately 21~25$

□ 10~15$ □ 16~20$ □ 21~25$ □ 26~30$ □ 30~35 $ □ Other

5. Feel free to write any comments, if you have any:

Appendix

Exit QuestionnaireII

Usability Questions

Productivity The flexible keyboard helps me be more productive.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
The flexible keyboard is useful to type.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
Feedback feel The flexible keyboard is responsive enough.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
Reduced key-clicking (typing) sound is comfortable for me	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
I am able to complete my task quickly using the flexible keyboard	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
Ease of Use The flexible keyboard is easy to use	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
The flexible keyboard is comfortable for me	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
Mobile I believe the flexible keyboard is easy to carry.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
I believe the flexible keyboard is good to use with hand-held devices (i.e. PDA, Mobile computer etc.)	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
I believe the flexible keyboard is easy to maintain (i.e. clean up, water resistance etc.)	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree

Appendix

Ease of Learning					
It is easy to learn to use the flexible keyboard.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
I quickly became skillful with the flexible keyboard.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
Design					
The size of the flexible keyboard is satisfactory for me.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
The shape of the flexible keyboard is satisfactory for me.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
The color of the flexible keyboard is satisfactory for me.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
The material of the flexible keyboard is satisfactory for me.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
The weight of the flexible keyboard is satisfactory for me.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
Overall, the flexible keyboard is attractive for me.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
Satisfaction					
I would recommend the flexible keyboard to a friend.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
I like the flexible keyboard.	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
I feel I need to have the flexible keyboard	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
I feel comfortable using the flexible keyboard	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree
Overall, I am satisfied with the flexible keyboard	Strongly Disagree ☐	☐ Disagree	☐ Neutral	☐ Agree	☐ Strongly Agree

Appendix F: Demographic

Participant	Age	Gender	Dominant Hand	Experience of keyboard Use (years)	Using a computer (hr/day)	Keyboard type used most often
p1	23	M	R	13	5	S
p2	24	M	R	11	6	S
p3	21	M	R	9	5	L
p4	21	M	R	13	3	S
p5	25	M	R	12	6	S
p6	23	M	R	16	5	S
p7	22	F	R	10	5	L
p8	24	F	R	15	5	L
p9	20	F	R	11	5	S
p10	19	F	R	8	8	S
p11	22	F	R	8	4	L
p12	29	F	R	24	3	S
Count or Mean (SD)	22.75(2.63)	6 Female 6 Male	12 Right	12.5 (4.42)	5 (1.35)	8 Standard 4 Laptop

Appendix G: Average (SD) score for dependent variables

Per Day, Shape and Hardness

** Subjective measure*

Dependent variable	Day		Shape		Hardness		
	D1	D2	Circle	Square	Hard	Medium	Soft
NTS /wpm	34.00 (7.07)	35.94 (7.78)	33.74 (6.47)	36.21 (7.54)	33.02 (6.54)	36.56 (7.06)	35.34 (7.46)
GTS /wpm	39.73 (8.43)	39.68 (9.98)	38.88 (8.50)	40.53 (9.09)	37.77 (8.22)	40.93 (8.54)	40.42 (9.56)
ERR /wpm	5.72 (3.73)	3.74 (3.12)	5.14 (3.55)	4.32 (2.67)	4.74 (3.30)	4.37 (2.85)	5.08 (3.37)
MW	6.70 (5.69)	4.82 (4.97)	6.01 (4.40)	5.50 (5.24)	7.85 (7.30)	4.33 (2.28)	5.09 (2.42)
MSW	74.44 (49.95)	47.89 (41.50)	67.36 (47.39)	54.96 (34.18)	56.92 (38.73)	58.73 (38.92)	67.84 (47.22)
EW	0.65 (1.08)	0.43 (0.75)	0.43 (0.54)	0.65 (0.89)	0.48 (0.58)	0.50 (0.77)	0.64 (0.87)
JW	3.47 (5.82)	2.69 (6.18)	2.88 (4.41)	3.29 (6.75)	5.46 (8.72)	1.48 (2.30)	2.30 (2.93)
SW	0.62 (1.30)	0.19 (0.68)	0.36 (0.75)	0.46 (0.95)	0.46 (0.79)	0.48 (0.96)	0.29 (0.82)
Pr1*	2.32 (1.22)	2.68 (1.06)	2.32 (0.88)	2.68 (0.96)	2.25 (0.85)	2.96 (0.94)	2.29 (0.86)
Pr2*	2.22 (1.02)	2.78 (1.00)	2.38 (0.76)	2.63 (0.88)	2.33 (0.72)	2.75 (0.91)	2.42 (0.82)
Fb1*	2.67 (1.29)	2.68 (1.17)	2.38 (0.94)	2.97 (0.99)	2.27 (1.00)	2.96 (1.01)	2.79 (0.91)
Fb2*	3.17 (1.21)	3.18 (1.14)	3.19 (1.15)	3.15 (1.13)	3.19 (1.21)	3.08 (1.19)	3.25 (1.05)
Eu1*	1.65 (0.75)	2.01 (0.76)	1.67 (0.52)	2.00 (0.63)	1.63 (0.54)	2.10 (0.63)	1.77 (0.55)
Eu2*	2.28 (1.09)	2.74 (0.92)	2.29 (0.74)	2.72 (0.92)	2.19 (0.78)	2.85 (0.87)	2.48 (0.83)
El1*	2.69 (1.15)	3.04 (0.97)	2.65 (0.88)	3.08 (1.00)	2.67 (0.99)	3.17 (0.89)	2.77 (0.97)
El2*	2.90 (1.00)	3.19 (0.93)	2.94 (0.84)	3.15 (0.91)	2.98 (0.87)	3.25 (0.82)	2.92 (0.94)
Sf1*	2.65 (1.21)	2.81 (1.02)	2.58 (0.93)	2.88 (0.94)	2.38 (0.88)	3.10 (0.96)	2.71 (0.88)
Sf2*	2.07 (0.92)	2.47 (0.90)	2.11 (0.66)	2.43 (0.80)	1.98 (0.65)	2.63 (0.70)	2.21 (0.76)

Per Trials (interaction between Shape and Hardness)

** Subjective measure*

Independent Variable	K1 (H-C)	K2 (H-S)	K3 (M-C)	K4 (M-S)	K5 (S-C)	K6 (S-S)
NTS /wpm	30.88 (5.31)	35.17 (7.15)	34.80 (5.79)	38.32 (7.99)	35.54 (7.61)	35.14 (7.64)
GTS /wpm	36.04 (7.88)	39.50 (8.52)	39.46 (7.73)	42.39 (9.38)	41.13 (9.66)	39.71 (9.84)
ERR /wpm	5.16 (3.66)	4.33 (3.01)	4.67 (3.49)	4.07 (2.13)	5.58 (3.76)	4.57 (3.00)
MW	7.83 (6.50)	7.88 (8.32)	4.88 (2.89)	3.79 (1.37)	5.33 (2.36)	4.84 (2.57)
MSW	64.29 (44.26)	49.54 (32.53)	62.42 (47.28)	55.04 (30.02)	75.38 (53.33)	60.31 (41.17)
EW	0.46 (0.62)	0.50 (0.56)	0.33 (0.39)	0.67 (1.01)	0.50 (0.60)	0.78 (1.08)
JW	4.33 (6.46)	6.58 (10.69)	2.17 (2.96)	0.79 (1.10)	2.13 (2.81)	2.48 (3.15)
SW	0.46 (0.58)	0.46 (0.99)	0.21 (0.33)	0.75 (1.29)	0.42 (1.14)	0.16 (0.24)
Pr1*	1.92 (1.06)	2.58 (1.18)	2.75 (1.11)	3.17 (0.92)	2.29 (1.00)	2.29 (1.30)
Pr2*	2.17 (1.13)	2.50 (1.10)	2.58 (1.06)	2.92 (0.93)	2.38 (0.71)	2.46 (1.22)
Fb1*	1.83 (0.87)	2.71 (1.33)	2.63 (1.10)	3.29 (1.30)	2.67 (1.09)	2.92 (1.25)
Fb2*	3.25 (1.19)	3.13 (1.30)	3.08 (1.25)	3.08 (1.21)	3.25 (1.19)	3.25 (0.99)
Eu1*	1.42 (0.50)	1.83 (0.87)	1.96 (0.75)	2.25 (0.74)	1.63 (0.58)	1.92 (0.93)
Eu2*	1.88 (0.74)	2.50 (1.14)	2.71 (1.12)	3.00 (0.88)	2.29 (0.81)	2.67 (1.13)
El1*	2.38 (1.10)	2.96 (1.12)	2.88 (1.03)	3.46 (0.88)	2.71 (0.91)	2.83 (1.17)
El2*	2.79 (0.98)	3.17 (0.96))	3.13 (0.95)	3.38 (0.82)	2.92 (0.88)	2.92 (1.18)
Sf1*	2.17 (1.01)	2.58 (1.18)	2.92 (1.14)	3.29 (1.04)	2.67 (1.01)	2.75 (1.11)
Sf2*	1.83 (0.82)	2.13 (1.08)	2.42 (0.83)	2.83 (0.70)	2.08 (0.78)	2.33 (1.09)

Appendix H: P-values for Shapiro-Wilk's Normality Test (by day)

(** Marked values indicate normal data.)

	DAY	*K1 Hard, Circle	K2 Hard, Square	K3 Medium, Circle	K4 Medium, Square	K5 Soft, Circle	K6 Soft, Square	% Normal Trials
NTS	1	0.9744	0.94	0.6762	0.6628	0.8395	0.5997	**100% ****
	2	0.0945	0.3173	0.6518	0.8417	0.3177	0.4576	**100%****
GTS	1	0.6563	0.6868	0.8912	0.5672	0.1088	0.3243	**100% ****
	2	0.0863	0.138	0.1272	0.9317	0.8626	0.3617	**100%****
ERR	1	0.3198	0.5318	0.2485	0.9799	0.5694	0.3537	**100% ****
	2	0.02	0.0059	0.3123	0.1853	0.1558	0.0181	**50%****
MW	1	0.3821	<0.0001	0.1706	0.1586	0.8251	0.0613	**83% ****
	2	<0.0001	0.0011	0.6143	0.548	0.2504	0.0358	**50%****
MSW	1	0.364	0.9583	0.5111	0.9963	0.7832	0.5936	**100% ****
	2	0.07	0.0041	0.2407	0.085	0.1127	0.0177	**67%****
EW	1	0.019	0.0005	0.0024	<0.0001	0.0005	0.027	0%
	2	<0.0001	0.0002	<0.0001	0.0017	0.0005	0.0017	0%
JW	1	0.0018	0.0005	0.0034	0.0023	0.0255	0.425	17%
	2	<0.0001	0.0001	0.0002	0.0004	0.0001	0.0002	0%
SW	1	0.0021	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0%
	2	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0%
Pr1	1	0.0001	0.0203	0.0060	0.0588	0.0180	0.0004	17%
	2	0.0014	0.0024	0.0766	0.0462	0.0317	0.0060	17%
Pr2	1	0.0015	0.1343	0.0153	0.0032	0.0100	0.0088	17%
	2	0.1874	0.0224	0.0042	0.0097	0.0330	0.0637	33%
Fb1	1	0.0053	0.0783	0.0060	0.0419	0.1720	0.0062	0%
	2	0.0010	0.0317	0.0797	0.0323	0.1874	0.2431	33%
Fb2	1	0.0708	0.2759	0.0462	0.1874	0.2482	0.0317	**67%****
	2	0.4396	0.0317	0.4950	0.1720	0.0824	0.1343	**83%****
Eu1	1	<0.0001	0.0153	0.0005	0.0005	0.0001	0.0098	0%
	2	0.0002	0.0043	<0.0001	0.0043	0.0598	0.0115	17%
Eu2	1	0.0002	0.0251	0.1227	0.0183	0.0558	0.0332	33%
	2	<0.0001	0.0008	0.0005	0.0317	0.0058	0.0317	0%
El1	1	0.0111	0.0628	0.1232	0.0224	0.1333	0.0107	**50%****
	2	0.1343	0.0038	0.0113	0.2482	0.0598	0.0330	**50%****
El2	1	0.1369	0.1227	0.1227	0.0513	0.0052	0.0038	**67%****
	2	0.0513	0.1333	0.0125	0.0797	0.1333	0.0330	**67%****
Sf1	1	0.0113	0.2431	0.0144	0.0183	0.0598	0.0476	33%
	2	0.0061	0.0803	0.0016	0.0224	0.4333	0.0479	33%
Sf2	1	0.0002	0.0153	0.0058	0.0513	0.0056	0.0088	17%
	2	0.0003	0.1599	0.0056	0.0183	0.0180	0.0598	33%

**Trial combination (shape of contact point, hardness of material)*

Appendix I: Tkey HSD

Significant Differences for Hardness

(Means with the same letter are not significantly different)

Dependent variables	Hardness	Mean	Significant Difference	Dependent variables	Hardness	Mean	Significant Difference
NTS	Medium	36.5575	A	Fb1*	Medium	2.9583	A
	Soft	35.3394	A		Soft	2.7917	A
	Hard	33.0242	B		Hard	2.2708	B
GTS	Medium	40.9250	A	Eu1*	Medium	2.1042	A
	Soft	35.3394	A		Soft	1.7708	B
	Hard	33.0242	B		Hard	1.6250	B
MW	Hard	7.8542	A	Eu2*	Medium	2.8542	A
	Soft	5.0833	B		Soft	2.4792	B
	Medium	4.3333	B		Hard	2.1875	B
JW	Hard	5.4583	A	El1*	Medium	3.1667	A
	Soft	2.3125	B		Soft	2.7708	A B
	Medium	1.4792	B		Hard	2.6667	B
Pr1*	Medium	2.9583	A	Sf1*	Medium	3.1042	A
	Soft	2.2917	B		Soft	2.7083	B
	Hard	2.2500	B		Hard	2.3750	B
Pr2*	Medium	2.7500	A	Sf2*	Medium	2.6250	A
	Soft	2.4167	A B		Soft	2.2083	B
	Hard	2.3333	B		Hard	1.9792	B

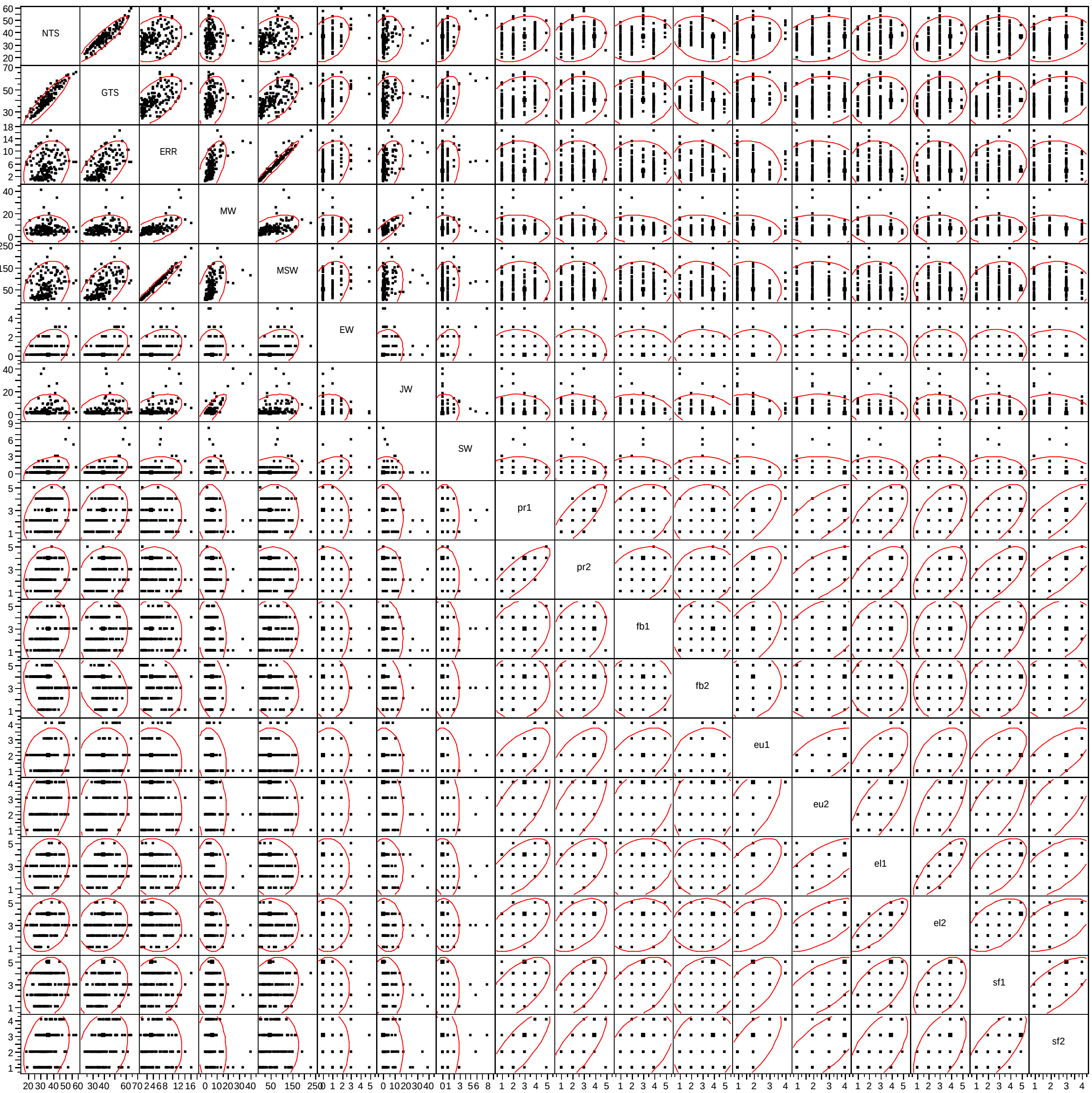
**Marked denote subjective measure*

Significant Differences for an Interaction of Shape & Hardness

(Means with the same letter are not significantly different)

Dependent variables	Interaction	Mean	Significant Difference	Keyboard type
NTS	S – M	38.32	A	K4
	C – S	35.54	B	K5
	S – H	35.17	B	K2
	S – S	35.14	B	K6
	C – M	34.80	B	K3
	C – H	30.87	C	K1
GTS	S – M	42.39	A	K4
	C – S	41.13	A B	K5
	S – S	39.71	A B	K6
	S – H	39.50	B	K2
	C – M	39.46	B	K3
	C – H	36.04	C	K1
JW	S – H	6.58	A	K2
	C – H	4.33	A B	K1
	S – S	2.48	B C	K6
	C – M	2.17	B C	K3
	C – S	2.13	B C	K5
	S – M	0.79	C	K4

Appendix J: Correlation scatter plot

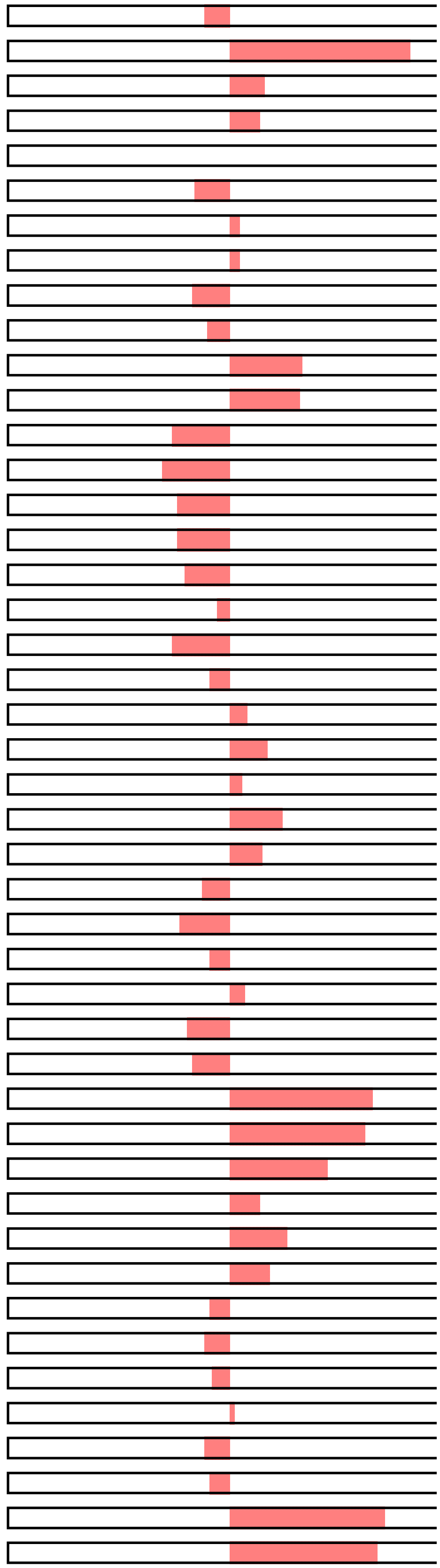


Appendix K: liner correlation table

Variable	by Variable	Correlation	Signif Prob	Plot Corr
GTS	NTS	0.9276	0.0000	
ERR	NTS	0.2850	0.0005	
ERR	GTS	0.6225	0.0000	
MW	NTS	0.0461	0.5836	
MW	GTS	0.2780	0.0007	
MW	ERR	0.6168	0.0000	
MSW	NTS	0.2799	0.0007	
MSW	GTS	0.6115	0.0000	
MSW	ERR	0.9825	0.0000	
MSW	MW	0.4727	0.0000	
EW	NTS	0.3574	0.0000	
EW	GTS	0.4467	0.0000	
EW	ERR	0.3975	0.0000	
EW	MW	0.1168	0.1631	
EW	MSW	0.3959	0.0000	
JW	NTS	0.1473	0.0781	
JW	GTS	0.3005	0.0003	
JW	ERR	0.4624	0.0000	
JW	MW	0.8262	0.0000	
JW	MSW	0.2985	0.0003	
JW	EW	0.0608	0.4693	
SW	NTS	0.4274	0.0000	
SW	GTS	0.4331	0.0000	
SW	ERR	0.2158	0.0094	
SW	MW	0.0175	0.8350	
SW	MSW	0.2082	0.0123	
SW	EW	0.4540	0.0000	
SW	JW	0.0089	0.9158	
pr1	NTS	0.3088	0.0002	
pr1	GTS	0.2692	0.0011	
pr1	ERR	0.0439	0.6017	
pr1	MW	-0.0971	0.2467	
pr1	MSW	0.0749	0.3721	
pr1	EW	-0.0261	0.7563	
pr1	JW	-0.1092	0.1925	
pr1	SW	-0.0200	0.8117	
pr2	NTS	0.2536	0.0022	
pr2	GTS	0.2041	0.0141	
pr2	ERR	-0.0076	0.9281	
pr2	MW	-0.1060	0.2062	
pr2	MSW	0.0152	0.8561	
pr2	EW	-0.0144	0.8640	
pr2	JW	-0.0726	0.3875	

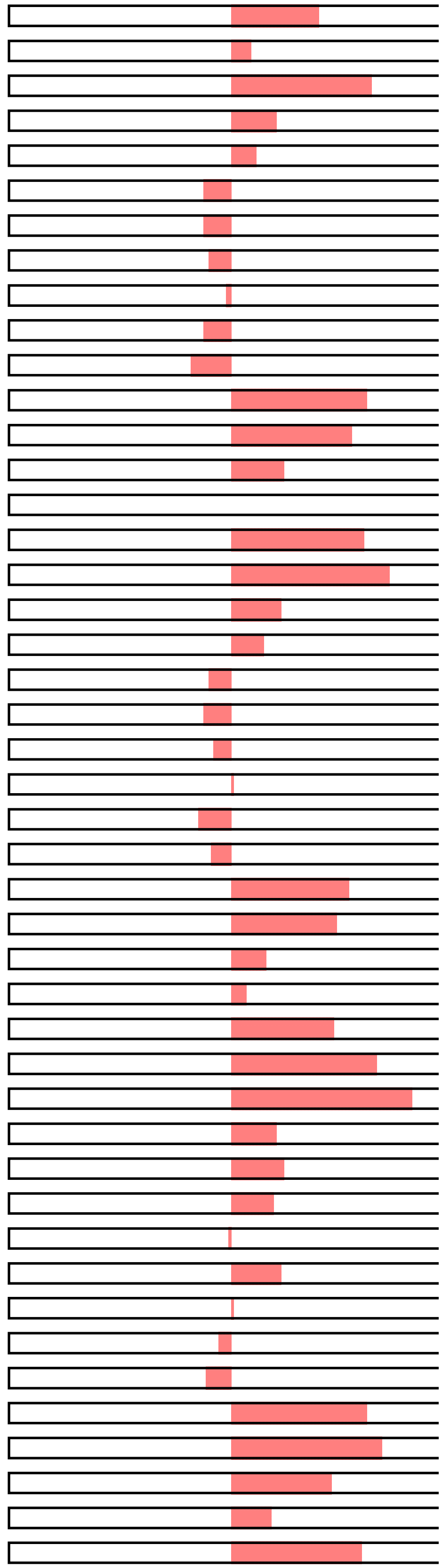
Appendix

Variable	by Variable	Correlation	Signif Prob	Plot Corr
pr2	SW	-0.1105	0.1874	
pr2	pr1	0.8132	0.0000	
fb1	NTS	0.1623	0.0519	
fb1	GTS	0.1359	0.1043	
fb1	ERR	0.0087	0.9176	
fb1	MW	-0.1491	0.0745	
fb1	MSW	0.0487	0.5622	
fb1	EW	0.0457	0.5869	
fb1	JW	-0.1653	0.0478	
fb1	SW	-0.1006	0.2301	
fb1	pr1	0.3285	0.0001	
fb1	pr2	0.3244	0.0001	
fb2	NTS	-0.2520	0.0023	
fb2	GTS	-0.2936	0.0004	
fb2	ERR	-0.2255	0.0066	
fb2	MW	-0.2340	0.0048	
fb2	MSW	-0.1917	0.0213	
fb2	EW	-0.0483	0.5650	
fb2	JW	-0.2556	0.0020	
fb2	SW	-0.0857	0.3070	
fb2	pr1	0.0854	0.3090	
fb2	pr2	0.1741	0.0369	
fb2	fb1	0.0639	0.4467	
eu1	NTS	0.2368	0.0043	
eu1	GTS	0.1486	0.0754	
eu1	ERR	-0.1146	0.1714	
eu1	MW	-0.2201	0.0080	
eu1	MSW	-0.0789	0.3470	
eu1	EW	0.0775	0.3556	
eu1	JW	-0.1804	0.0305	
eu1	SW	-0.1630	0.0510	
eu1	pr1	0.6493	0.0000	
eu1	pr2	0.6130	0.0000	
eu1	fb1	0.4491	0.0000	
eu1	fb2	0.1397	0.0949	
eu2	NTS	0.2629	0.0015	
eu2	GTS	0.1812	0.0297	
eu2	ERR	-0.0858	0.3067	
eu2	MW	-0.1020	0.2236	
eu2	MSW	-0.0703	0.4026	
eu2	EW	0.0252	0.7642	
eu2	JW	-0.1041	0.2142	
eu2	SW	-0.0826	0.3252	
eu2	pr1	0.7032	0.0000	
eu2	pr2	0.6657	0.0000	



Appendix

Variable	by Variable	Correlation	Signif Prob	Plot Corr
eu2	fb1	0.4022	0.0000	
eu2	fb2	0.1002	0.2320	
eu2	eu1	0.6312	0.0000	
el1	NTS	0.2038	0.0143	
el1	GTS	0.1218	0.1459	
el1	ERR	-0.1144	0.1722	
el1	MW	-0.1130	0.1775	
el1	MSW	-0.0960	0.2521	
el1	EW	-0.0190	0.8213	
el1	JW	-0.1211	0.1482	
el1	SW	-0.1796	0.0312	
el1	pr1	0.6137	0.0000	
el1	pr2	0.5400	0.0000	
el1	fb1	0.2432	0.0033	
el1	fb2	0.0072	0.9316	
el1	eu1	0.5955	0.0000	
el1	eu2	0.7123	0.0000	
el2	NTS	0.2258	0.0065	
el2	GTS	0.1478	0.0772	
el2	ERR	-0.0940	0.2625	
el2	MW	-0.1138	0.1744	
el2	MSW	-0.0741	0.3773	
el2	EW	0.0171	0.8387	
el2	JW	-0.1353	0.1060	
el2	SW	-0.0806	0.3366	
el2	pr1	0.5283	0.0000	
el2	pr2	0.4795	0.0000	
el2	fb1	0.1660	0.0468	
el2	fb2	0.0786	0.3493	
el2	eu1	0.4662	0.0000	
el2	eu2	0.6602	0.0000	
el2	el1	0.8125	0.0000	
sf1	NTS	0.2086	0.0121	
sf1	GTS	0.2457	0.0030	
sf1	ERR	0.1934	0.0202	
sf1	MW	-0.0006	0.9947	
sf1	MSW	0.2261	0.0064	
sf1	EW	0.0210	0.8024	
sf1	JW	-0.0551	0.5122	
sf1	SW	-0.1064	0.2044	
sf1	pr1	0.6164	0.0000	
sf1	pr2	0.6803	0.0000	
sf1	fb1	0.4551	0.0000	
sf1	fb2	0.1856	0.0259	
sf1	eu1	0.5853	0.0000	



Appendix

Variable	by Variable	Correlation	Signif Prob	Plot Corr
sf1	eu2	0.6544	0.0000	
sf1	el1	0.6004	0.0000	
sf1	el2	0.4961	0.0000	
sf2	NTS	0.3102	0.0002	
sf2	GTS	0.2625	0.0015	
sf2	ERR	0.0239	0.7765	
sf2	MW	-0.1298	0.1210	
sf2	MSW	0.0560	0.5052	
sf2	EW	0.0312	0.7102	
sf2	JW	-0.1190	0.1553	
sf2	SW	-0.0069	0.9344	
sf2	pr1	0.8097	0.0000	
sf2	pr2	0.7644	0.0000	
sf2	fb1	0.4379	0.0000	
sf2	fb2	0.1165	0.1643	
sf2	eu1	0.7105	0.0000	
sf2	eu2	0.7070	0.0000	
sf2	el1	0.6021	0.0000	
sf2	el2	0.5184	0.0000	
sf2	sf1	0.7218	0.0000	