Dependence of typing speed and accuracy
on device type and familiarity

by
Kim E. Veldee

Submitted to the
Department of Mechanical Engineering
In Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

June 2019

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Abstract

Typing has become increasingly present in modern lives through its uses in laptops, phones, tablets, and other consumer electronics. Current computers encourage high typing speeds by implementing mistake corrections such as "backspace" or "delete" keys, functions that were previously done by cross-outs or complete rewrites of the entire page. These mistake correction options have minimized the consequences for typing errors and have caused typists to place less importance on typing accuracy. As more models of electronic devices are placed on the market, users build familiarity with and skills for their specific device model.

Twelve participants were asked to complete a series of thirty-two typing tests on various laptop keyboards and mobile phones. Measurements were taken of typing speed and accuracy on familiar and unfamiliar keyboards for both laptops and phone keyboards, and specific mistake types were counted and recorded. The effects of Autocorrection were observed through the transcription of multiple passages with and without Autocorrection enabled. The results were compared between device types (phone vs. laptop keyboards), level of familiarity (personal vs. unfamiliar keyboards), presence of Autocorrection, participant sex, and undergraduate major. Participant sex and undergraduate major did not significantly affect typing speeds on phones or laptop keyboards. Participants typed approximately 20% faster on laptop keyboards than on phone keyboards. Participants decreased in speed when typing on unfamiliar phone and laptop keyboards (approximately 46% slower on phones and 2.7% to 5.5% slower on laptops) and typed about 10% slower when prohibited from utilizing the "backspace" or "delete" keys. Misspellings were consistently the most frequent mistake type and account for approximately 50% of mistakes, along with bad ordering on laptops (approximately 30%) and incorrectly-located spaces on phones (approximately 20%). Participants who regularly enable Autocorrect typed about 20% slower on phones when Autocorrection was disabled.

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1. Introduction

Technology has become deeply ingrained in the modern lifestyle. Of the total U.S. population in 2018, 95% own cell phones and 73% own computers, both of which indicate a high level of dependency of individuals on their electronics ("Demographics of Mobile Device Ownership and Adoption in the United States", 2018). It is natural that increased familiarity and skill would come along with such high levels of dependency. When the typewriter was introduced, the jumbled QWERTY layout slowed typists down and mistakes had to be fixed either with cross-throughs, white-out, or complete rewrites. Today, as individuals type more and more frequently, the QWERTY orientation has become the learned standard that allows individuals to type at ever-increasing speeds and fix mistakes with a few extra key clicks.

The ability to fix one's mistakes while typing has led to a widespread dependency on technological crutches such as "Backspace", "Delete", and "Autocorrection" functions. Mistake-erasing functions, such as "Backspace" and "Delete", have increased inattention while typing by decreasing the consequences of mistakes and allowing them to be easily remedied. Typing aids, such as "Autocorrection", have been recently discussed as decreasing the spelling capabilities of adult individuals, causing them to be unable to spell trickier common words such as "necessary" and "embarrassed" ("Poor Spelling of 'Auto-Correct Generation' Revealed", 2012).

Typing has morphed from its original function of formalizing formally handwritten passages to a multifunctional technological tool that is utilized for numerous daily tasks. To determine how modern users interact with keyboards, participants were asked to do thirty-two individual typing tests using devices that varied in device type and familiarity. The participants were requested to complete tests on their personal phones and personal laptops, as well as corresponding unfamiliar devices. The tests were used to measure typing speeds, accuracy percentages, and specific mistake types to be compared across participant characteristics, device type, and device familiarity.

2. Background

2.1 Computer Keyboard History

The history of typing keyboards stretches back to the invention of the typewriter in 1868. E. Remington and Sons invented the Sholes & Glidden Type-Writer which allowed users to write at a pace that far exceeded that of handwriting. The typewriter was a completely mechanical system primarily made up of levers and springs. When a key was depressed, the lever lifted the desired piece of block of metal with a raised piece of type on it. A ribbon of inked cloth was lifted immediately before the type contacted the paper, causing the type to make a printed impression upon impact. As the lever was retracted to its resting position, the carriage shifted the paper over to ready it for the next letter.

Initially, typing keyboards were designed to be in alphabetical order. This organization was chosen to help the user find the desired key quickly and logically, allowing them to type at the quickest possible rate. From this point forward, multiple theories arose and attempted to explain the change to the QWERTY keyboard layout. The commonly believed theory is that the

QWERTY layout, named by listing the sequence that tracks along the top row of the keyboard, maximized distance between common letter pairings such as 'an', 'he', and 'pr'. The theory argues that this layout was implemented to avoid mechanical jamming that would occur if nearby letters were pressed quickly after each other (Stamp, 2013).

However, recent research has argued against the popular mechanical jamming theory by first pointing out that, if the mechanical jamming theory was intended to decrease typing time, then 'e' and 'r' would be set far apart as 'er' is the fourth most popular letter pairing in the English language (Stamp, 2013). Koichi Yasuoka and Motoko Yasuoka, researchers from Japan's Kyoto University, argued that the typewriter keyboard design was inspired by the Hughes-Phelps Printing Telegraph and that the QWERTY layout was implemented to assist Sholes & Glidden's initial customer demographic: Morse receivers. (Yasuoka, Koichi, and Motoko Yasuoka, 2011)

As technology advanced, typewriters morphed into the computers that are used today. The mechanical levers and stamps have been replaced with digital keys yet the QWERTY letter organization remains intact. Jimmy Stamp from Smithsonian.com explains why the layout has persisted, saying "Form follows function and the keyboard trains the typist" (Stamp, 2013). Individuals who have been trained on one keyboard are unlikely to retrain to use an unfamiliar and uncommon keyboard layout. Therefore, QWERTY is solidified as the standard keyboard layout.

2.2 A Brief Description of Modern Typing

Nowadays, typing is commonly used on personal mobile phones and laptops, the two devices that investigated in this study. Users may type on phones to complete tasks such as sending an instant message, sending emails, looking up content on a search engine, or posting on social media. When typing on a phone, individuals can choose to designate various methods for typing. The most commonly used method resembles computer typing technique where the user hunts and pecks for keys, and on phones this is most commonly done using the typist's thumbs. Other common methods for typing on a mobile phone include voice texting (where the user verbalizes the message content and the phone transcribes the message) and Swype (where the user completes one continuous swipe approximately across all letters of the word to be typed and the phone predicts the word that the user was intending to type).

Like phone users, laptop users may type on their devices to instant message, email, look up content on a search engine, or post on social media. Laptops are also commonly used in school and workplaces where, for example, a student is expected to type assignments or reports on their computer. Individuals who are interested in computer programming may type hundreds of lines of computer code per project.

2.3 Relevant Prior Research

2.3.1 On the Relationship of Sex with Typing Speed and Accuracy

There are physiological differences between males and females. Among these differences is finger thickness, where male fingers are found to be approximately 20% larger in thickness than female fingers. Male fingers are also found to be approximately 10% longer for men than for women (Attwood, 2004).

Dennis J. LaBonty investigated the relationship of finger size to computer keyboard typing speed and accuracy and published his work in 1981. LaBonty's experiment found that there are no relationships between finger length or finger width and typing speed or accuracy for either males or females. LaBonty also found no correlation between male and female typing speeds (LaBonty 1981).

2.3.2 On the Experiential Differences between Hard and Soft Keyboards

Keyboards that consist of physical moving keys imbedded in a keyboard chassis are considered hard keyboards. Soft keyboards replace hard keyboards by displaying a digital keyboard on a screen or flat surface. Hard keyboards are often found on desktop or laptop keyboards, and soft keyboards are often found on phones, iPads, or tablets.

Seckin Celik investigated the factors which influence key entry speed on hard and soft keyboards and mapped those factors to their impacts on the typing experience. He emphasized two main factors that are critical to typists' success when typing on hard keyboards: tactile feedback on finger position and auditory feedback when a key is pressed (Celik, 2013). These two factors are absent when typing on soft keyboards unless the typist actively enabled keyboard clicks in their phone settings, which none of the participants in the following experiment did. Celik found that typists typed more quickly on hard keyboards than on soft keyboards. He also found that position information (raised bumps indicating the finger position to the typist) had a main effect on task completion time and total glance time on the areas of interest and was more impactful when audio feedback (clicking when a key was pressed) was implemented. These added characteristics to soft keyboards allowed them to mimic hard keyboards and illustrated the impact of soft keyboard on typing speed and experience.

Stephen Brewster et. al further investigated the impact of tactile feedback on typing speed, where twelve participants were given ten minutes to transcribe as many lines of provided poems as possible, with and without tactile feedback enabled. Their number of lines entered, total errors, and numbers of errors uncorrected were recorded. It was found that by enabling tactile feedback more lines were typed, less errors were performed, and more errors were corrected. The study suggests "that the tactile feedback generally increased their awareness of mis-hit keys so that they could go back and correct them" (Brewster, 2007).

The combination of these two citations proves that typists are generally quicker on hard keyboards than on soft keyboards and, to increase typing speed on soft keyboards, characteristics of hard keyboards such as auditory feedback and tactile response indicate finger position should be implemented.

2.3.3 *On the Effect of Keyboard Size on Typing Speed*

Andrew Sears et. all investigated the effects of touchscreen keyboard size on typing speed by exposing participants to four keyboard sizes ranging from 6.8 cm to 24.6 cm wide. Both novice and experienced users typed faster on the larger keyboard than on the smaller one, with typing speeds on the larger keyboard being approximately 20 W.P.M. and 32 W.P.N. and on the smaller keyboard being approximately 10 W.P.M. and 21 W.P.M. for novices and experts respectively. The drawn conclusions show that typing speeds decrease when keyboard sizes decrease (Sears, 1993).

2.4 Laptop Keyboard Specifics

The keyboards used in the present study were Dell keyboards, MacBook Pro keyboards, and AmazonBasics keyboards. Two models of MacBook Pro keyboards, the scissor and butterfly mechanisms, are described in the subsequent sections. The measured technical details for the four keyboard types are compared in Table 2.1.

Table 2.1: Technical details by laptop keyboard type

	Keyboard dimensions		Key dimensions				
Keyboard type	**Width[1]**	**Depth**	**Width**	**Depth**	**Height (up)[2]**	**Height (down)**	**Distance between keys**
Dell: scissor mech.	273	90	15	14.5	1	0	3.5
MacBook Pro: scissor mech.	273	95	16	15	1.2	0	3.75
MacBook Pro: butterfly mech.	275	95	17	16.5	0.4	0	2.3
AmazonBasics	282	98	14.5	14.5	2.8	0	4.5

All dimensions in mm. Typical data shown. [1] Keys beyond the shift key were disregarded during measurements. [2] Measured from surface of keyboard.

The AmazonBasics keyboard, use in this study as the unfamiliar keyboard in laptop keyboard testing, differs from the other three keyboard types in its larger keyboard footprint, smaller individual key dimensions, and higher key height. The Dell models are considered to be most similar to the AmazonBasics keyboard as they use plastic for both the keyboard chassis and individual keys, whereas both MacBook Pro models use an aluminum chassis and plastic keys (Dell, "*Innovative Material Choices*") ("*MacBook Environmental Report*", 2009]. Dell models and the AmazonBasics keyboard are also close in individual key width and height (approximately 14.5 mm).

The MacBook Pro scissor mechanism keyboards are considered next most similar to the AmazonBasics because, when compared to the butterfly mechanisms, the scissor mechanisms have higher key heights and larger key distances between individual keys. These characteristics are shared with the AmazonBasics keyboard. The MacBook Pro butterfly mechanism keyboards are considered the least similar to the AmazonBasics because it significantly differs in individual key width, depth, as height, as well as distance between keys.

In the trials to follow, MacBook Pro and Dell users will be identified independently to observe how design similarities between keyboards affect changes in typing speed and accuracy when typing on an unfamiliar keyboard.

2.4.1 Dell Keyboard

A scissor switch mechanism sits under each square key in a Dell keyboard, with multiple scissors sitting under larger rectangular keys such as the spacebar and shift key. The linkages guide the key straight down onto a silicone or rubber dome to signal to the computer that a key has been pressed, then the linkage reverses direction to reset the key to its upright position. Scissor switch mechanisms are common in other laptop models as well, such as older generations of Apple keyboards (Berger, 2016).

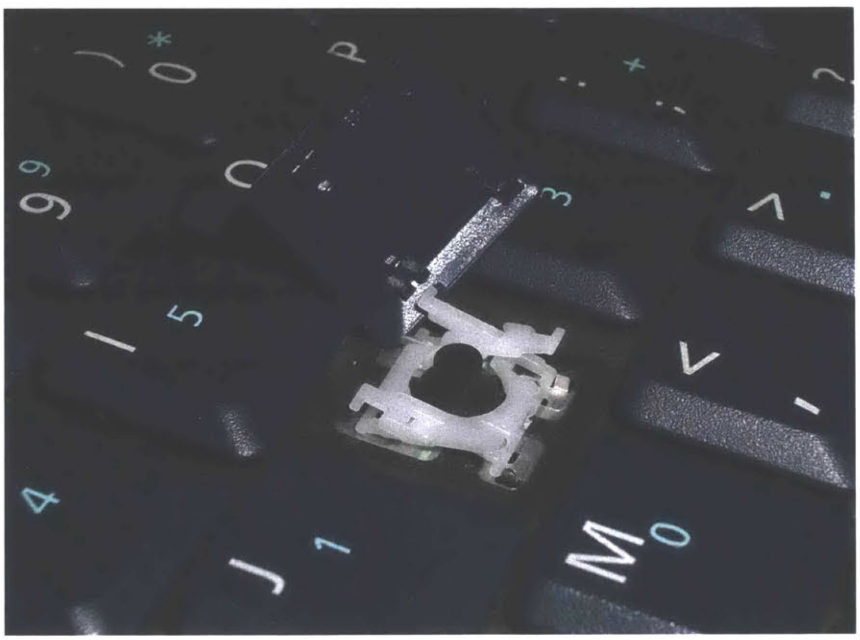

Figure 2.1: Example of the internal mechanism of a scissor switch keyboard (Berger, 2016)

2.4.2 Apple's Scissor Mechanism Keyboard

The scissor switch mechanism described in Section 2.4.1 is also used in older models of MacBook Pro laptops (prior to 2016 models). The mechanism is shown in Figure 2.2. Unfortunately, Apple's scissor mechanism allowed for kepcaps to tilt if the typist hit the key off-center, which often resulted in nearby keys also being depressed. The scissor mechanism was also prone to sticky or dead keys due to detritus accumulation below the keycap. Apple recently replaced the scissor switch mechanism with a new butterfly mechanism that better stabilized the key cap and increase typist precision (D'Onfro, 2015).

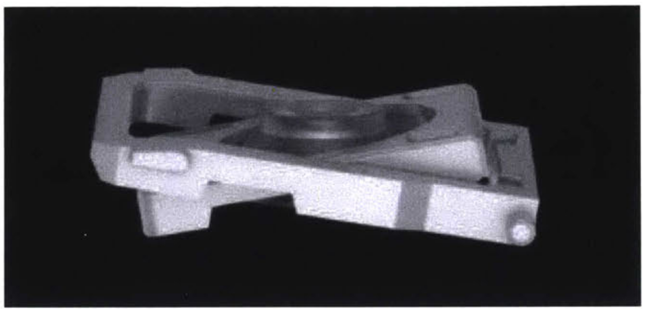

Figure 2.2: Traditional scissor mechanism for MacBook Pro

2.4.3 Apple's Butterfly Mechanism Keyboard

The butterfly keyboard was designed by Apple in order to offer more stable keys with a lower profile, designed to offer a more comfortable tying experience. Key height was decreased in order to reduce the accumulation of dust and detritus in the area under the keys. Previous keyboard designs sported a scissor-link lifting method (discussed in Section 2.4.2) and were prone to key failures due to dust and particle infiltration under the key, resulting in an increased required stroke force and more frequent unresponsive keys.

Apple filed for a patent on the butterfly keyboard design in September of 2014. The patent was filed under the label "Low-travel key mechanisms using butterfly hinges" and was granted under the patent number US 9502193B2 (Niu, 2016). The design featured a butterfly hinge hidden under each key that had a depression stroke between 0.1 mm and 2 mm. The cross-sectional view of the butterfly keyboard as submitted in the patent application is shown in Figure 2.3.

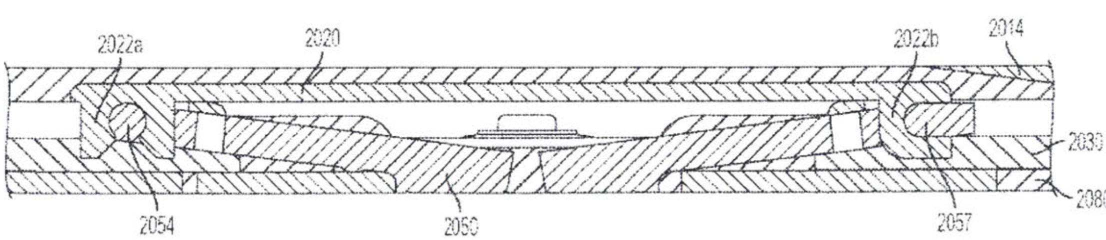

Figure 2.3: Section view of originally patented butterfly keyboard. The butterfly hinge (2050) is fastened under the middle of the letter key and rotates to lower the keycap (2014) to depress the middle button. The key's low profile and hard-to-access sliding pin (2057) work to prevent dust and detritus from jamming the keys.

Apple's mid-2018 update of the butterfly keyboard included a membrane placed between the individual letter and the structure's resting surface. The membrane's advertised intention was to further prevent detritus ingress and soften the contact noise of individual letters. Users have also mentioned that the membrane provides extra bounce to the keys and assists the depressed key in returning to its upright and resting position. Apple filed for a patent in 2016 under the label "Ingress prevention for keyboard", which is currently under review. The cross-sectional view of the butterfly keyboard with protective membrane as submitted in the patent application is shown in Figure 2.4.

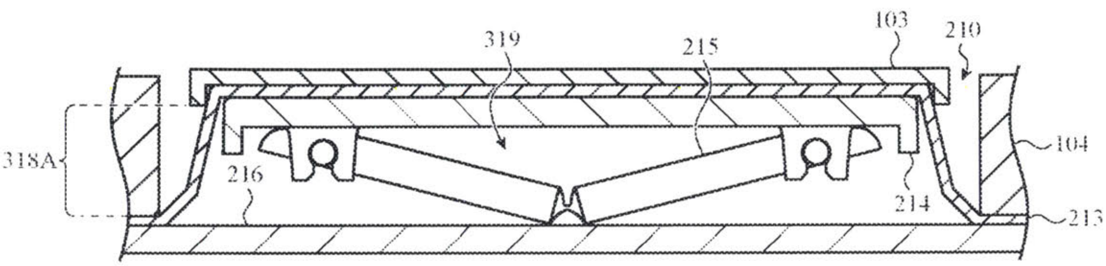

Figure 2.4: Section view of modified butterfly keyboard with membrane. The membrane (213) is fastened between the structure's resting surface and the keyboard layout web (104) that defines all key positions. The membrane prevents particles from blocking the butterfly hinge's path of motion and jamming the key.

Unfortunately for Apple, the butterfly keyboard has introduced new methods of key failure. Three lawsuits have been pursued because of the keyboards' tendencies to type doublets (repeated letters for a single key depression) and provide depression resistance. Instead of the keys refusing to lower as a result of invasive particles under the key, Apple's butterfly keyboard keys jam mechanically when the pin refuses to slide through the slot (2057 in Figure 2.4).

Many owners of MacBook Pros with the butterfly keyboard have been vocal about their negative experience in switching to the new keyboard type, expressing frustrations about the dead keys, sticky keys, and unintended doublets (Clover, 2019) (Lloyd, 2019). Home remedies to the dead keys and doublet-typing include blowing on the keys with compressed air ("*How to Clean the Keyboard of Your MacBook or MacBook Pro*"), wedging a piece of double-sided tape under the letter cap (Yoo, 2016), and sliding a toothpick around each key to clear its edges ("*How To Fix Sticky Keyboard Keys on a MacBook*"). In an attempt to win back its disgruntled consumers, Apple launched a keyboard service program to replace keys or keyboards for MacBooks and MacBook Pros from years 2015-2017 ("*Keyboard Service Program for MacBook and MacBook Pro*").

2.4.4 AmazonBasics Keyboard

The AmazonBasics wired keyboard is available for purchase from Amazon.com. The keyboard is depicted in Figure 2.5.

Figure 2.5: AmazonBasics wired keyboard

Both the keys and the chassis are made of black plastic, and the chassis encases both a silicone layer and electronics. After a key is pressed, it is lifted back to its upright position by raised bumps in the silicone layer that are referred to as dome switches ("*What Is a Dome-Switch Keyboard?*", 2017) The matrix of dome switches are shown in Figure 2.6.

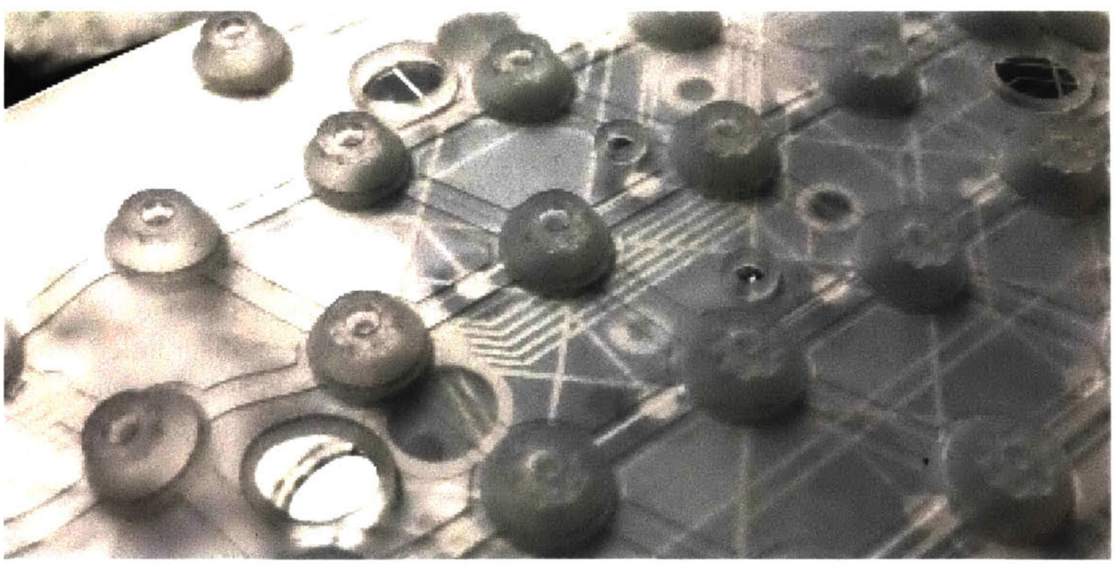

Figure 2.6: Silicone dome switches to raise depressed keys in AmazonBasics keyboard

2.5 Phone Keyboard Specifics

The phone models used in these experiments were iPhone and Droid Razr M. The dimensions for the various iPhone models are shown in Table 2.2.

Table 2.2: Technical details by iPhone generation

iPhone model	Phone dimensions		Screen dimensions	
	Width	Height	Width	Height
iPhone SE	58.6	123.8	49.9	88.5
iPhone 6S	67.1	138.3	58.5	104.1
iPhone 7	67.1	138.3	58.5	104.1
iPhone 8	67.3	138.4	58.5	104.1
iPhone 8+	78.1	158.4	68.5	121.8
iPhone X	70.9	143.6	61.8	133.7
iPhone XR	75.7	150.9	65.0	140.7

All dimensions in mm.

Table 2.2 shows the ranges in phone and keyboard dimensions for all iPhone generations that were used during these tests. All dimensions have increased throughout iPhone generations. The iPhone 7 was used as a representative of the iPhone models when comparing to the Droid Razr M, given that the iPhone 7's dimensions are in the middle of each dimension range across iPhone generations, The measured technical details for the iPhone 7 and Droid Razr M are compared in Table 2.3.

Table 2.3: Technical details by phone type

Keyboard type	Phone dimensions		Keyboard dimensions			Key dimensions	
	Width	Height	Width	Height	Distance between keys	Width	Height
iPhone 7	67	138	58	32.4	1	5	6.6
Droid Razr M	65.5	123	53	30	1	4.8	6

All dimensions in mm.

Table 2.3 shows that the Droid Razr M is smaller in all dimensions except for the distance between keys (where both keyboards had a distance of 1 mm between keys). In fact, the Droid Razr M is only larger than one iPhone generation that was used in testing: the iPhone SE. All other iPhone models are larger than the Droid Razr M in phone height and width. Comparing the keyboard sizes between the iPhone 7 and Droid Razr M show that the iPhone has a larger keyboard by 5 mm in width and 7.6 mm in height, and the footprint of each key is larger on the iPhone 7.

Beyond the differences in dimensions of the keys, keyboard, and phone itself, the two keyboards have some characteristics in common. In addition to the same QWERTY key layout, both keyboards have the shift key to the left of the ‘z’ key and the ‘backspace’ key to the right of the ‘m’ key. The key to shift to the numbers and punctuation keys lies in the bottom left corner of each keyboard.

However, another notable layout difference lies on the bottom line of each keyboard. The Droid Razr M keyboard offers quick selection of the period key, which sits between the spacebar and the ‘Go’ button. This is not offered on the iPhone and therefore may be unfamiliar for users who are accustomed to typing on an iPhone. Another difference is to the left of the space bar where the Droid Razr M keyboard places the forward slash instead of the emoji keyboard.

a) b)

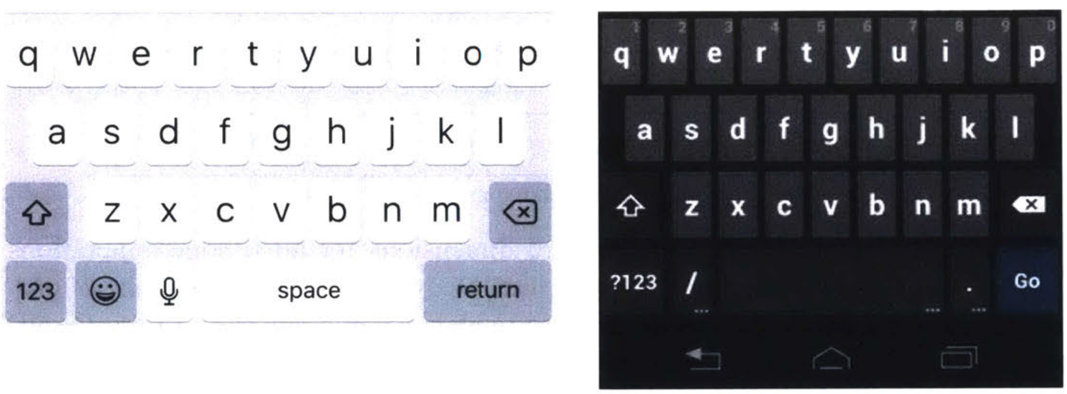

Figure 2.7: Visualizations of the iPhone keyboard (left) and Droid Razr M keyboard (right) (Eitelbach, 2017)

3. Methods

Twelve participants were recruited to perform typing trials on hard and soft keyboards. Each 2-hour trial session measured how typing speed, accuracy, and specific mistake type varied across device familiarity (comparing typing on the participant's personal keyboard to typing on an unfamiliar keyboard for both laptops and phones), device type (comparing typing on a laptop keyboard to typing on a phone keyboard), participant sex, and undergraduate major.

3.1 Subject Demographics

Twelve undergraduate students at MIT with f ages of 18 to 23 were recruited for this study. Seven of the twelve (58.3% of participants) identified as female. The age and sex distributions of participants are shown in Table 3.1. The undergraduate department count for the participants are shown in Table 3.2.

Table 3.1: Participant Age and Sex

	Participant Count	
Age	Male	Female
18	0	1
19	0	1
20	2	1
21	0	2
22	3	1
23	0	1

Table 3.2: Participant Count by MIT Undergraduate Department

Department	Participant Count
Biology	1
Computer Science and Engineering	4
Electrical Engineering and Computer Science	1
Environmental Engineering	1
Mechanical Engineering	4
Spanish	1

3.1.1 Subject Technology Demographics

All subjects personal laptops were either either MacBook Pros or Dell models. MacBook Pro models were grouped into those prior to 2016 and those after 2016, because of the significant change in keyboard design that Apple launched in 2016, as mentioned in Section 2.4 of the Background. The distribution of laptop models are found in Table 3.3. All subjects used an iPhone, with models listed in Table 3.3.

Table 3.3: Participant Count by Laptop and Phone Model

Laptop Model		Participant Count	iPhone Model	Participant Count
MacBook Pro	Models prior to 2016	3	iPhone SE	1
	Models 2016 and later	5	iPhone 6S	1
Dell	Latitude	1	iPhone 7	2
	Inspiron	1	iPhone 8 and 8+	3
	XPS	2	iPhone X and XR	5

3.2 Testing Procedure

Trials were conducted on the campus of the Massachusetts Institute of Technology in classrooms, public study rooms, libraries, and dorm rooms. The trial participant brought with them their personal laptop and personal mobile phone, both fully charged. They were then provided with an unfamiliar keyboard, an AmazonBasics Wired Keyboard, which was chosen because it varied in key height and material from the personal laptop keyboards for all subjects. Before each participant's testing session, the participant completed an informational survey to provide more details on the individual's background in technology use, as well as basic demographic information. The informational survey template is found in Appendix A.

Each participant's full testing session lasted approximately two hours long. During these trials, the participant was asked to complete a series of typing tests. The text of the passages used for the tests are in Appendix B. Before each newly introduced typing test, the participant was encouraged to complete practice runs until they felt comfortable with the typing test. Each testing session followed this schedule:

Test 1: Personal vs. unfamiliar phone keyboards: Passage transcription 1 of 3

1. Transcribe Phone Passage 1 with personal phone, Autocorrect enabled
2. Transcribe Phone Passage 2 with personal phone, Autocorrect disabled
3. Transcribe Phone Passage 3 with unfamiliar phone, Autocorrect enabled
4. Transcribe Phone Passage 4 with personal phone, Autocorrect enabled

Test 2: Personal vs. unfamiliar laptop keyboards: Passage transcription 1 of 2

5. Transcribe Laptop Passage 1 with personal keyboard
6. Transcribe Laptop Passage 2 with unfamiliar keyboard
7. Transcribe Laptop Passage 3 with personal keyboard
8. Transcribe Laptop Passage 4 with unfamiliar keyboard

Test 3: Personal laptop typing tests for speed, accuracy, and specific mistake types:

9. Complete typing test on keyhero.com at comfortable speed, maintaining accuracy
10. Complete typing test on keyhero.com to achieve highest typing speed possible
11. Complete typing test on keyhero.com without utilizing the backspace key

12-17: Repeat Steps 9-11 two more times for a total of three trials at each condition.

Test 4: Personal vs. unfamiliar phone keyboards: Passage transcription 2 of 3
18. Transcribe Phone Passage 1 with personal phone, Autocorrect disabled
19. Transcribe Phone Passage 2 with unfamiliar phone, Autocorrect enabled
20. Transcribe Phone Passage 3 with personal phone, Autocorrect enabled
21. Transcribe Phone Passage 4 with personal phone, Autocorrect disabled

Test 5: Personal phone typing test for speed and specific mistake type:
22. Complete typing test on TapTyping application at comfortable speed
23-24: Repeat Step 22 two more times for a total of three trials

Test 6: Personal vs. unfamiliar laptop keyboards: Passage transcription 2 of 2
25. Transcribe Laptop Passage 1 with unfamiliar keyboard
26. Transcribe Laptop Passage 2 with personal keyboard
27. Transcribe Laptop Passage 3 with unfamiliar keyboard
28. Transcribe Laptop Passage 4 with personal keyboard

Test 7: Personal vs. unfamiliar phone keyboards: Passage transcription 3 of 3
29. Transcribe Phone Passage 1 with unfamiliar phone, Autocorrect enabled
30. Transcribe Phone Passage 2 with personal phone, Autocorrect enabled
31. Transcribe Phone Passage 3 with personal phone, Autocorrect disabled
32. Transcribe Phone Passage 4 with unfamiliar phone, Autocorrect enabled

The experimental protocol was designed to minimize the effects of device and passage familiarity on the results. Gaining familiarity with the unfamiliar devices was prevented by scheduling as much time as possible between the repeated use of that unfamiliar device. Gaining familiarity with unfamiliar devices was also prevented by alternating conditions between familiar and unfamiliar devices, as done in the phone trials (Tests 1, 4, and 7) and laptop trials (Tests 2 and 6). For example, Tests 1, 4, and 7 all used the unfamiliar phone (Droid Razr M). These tests were strategically placed in the beginning, middle, and end of the testing period to ensure that there was a significant break before the participant once again typed on the unfamiliar keyboard and that the participant would type on their personal phone at least twice more before returning to the unfamiliar phone. This strategy was repeated for the laptop keyboard trials (Tests 2 and 6). Similarly to how device familiarity was prevented, passage familiarity was prevented by scheduling as much time as possible between repeated transcriptions of a single passage. This ensured that the participant did not have the chance to begin memorizing the passage, which would influence the participant's typing speed. The group of participants tested in this study is neither a complete nor truly random selection of test subjects at MIT or elsewhere. While every effort was made to reduce the effect of confounding factors, other factors such as inattention, testing fatigue, nerves, lack of sleep, and other personal external distractions may have affected individuals' typing speeds during trials. This study methodology could be extended and expanded to more subjects in order to allow for the results to be extended to the general population.

The following sections will describe the procedure for each test in more detail. They are organized by test type because the tests outlined above (Tests 1-7) include multiple trials of a single test. Section 3.2.1 describes the procedure for Tests 1, 4, and 7. Section 3.2.2 describes the procedure for Tests 2 and 6. Section 3.2.3 describes the procedure for Test 3. Section 3.2.4 describes the procedure for Test 5.

3.2.1 Speed by Familiarity of Phone and Presence of Autocorrection

Tests 1, 4, and 7 provided the participant with four passages of 55, 55, 58, and 57 words in length. Participants transcribed each passage with 1) personal mobile phone with their usual level of Autocorrect, 2) their personal mobile phone with Autocorrect turned off, and 3) an unfamiliar phone (Droid Razr M, 2012 release date) with Autocorrect enabled. The passages are included in Appendix C. The time taken for the participant to perfectly transcribe the passage was recorded . The four passages were transcribed by the participant three times under three different conditions (personal phone with Autocorrect, personal phone without Autocorrect, and unfamiliar phone with Autocorrect), each time changing the testing condition in order to mitigate the impact of passage familiarity on speed (see Section 3.2 for the testing timeline). The three trials were spaced out over the length of the two hour testing period to further decrease the impact of passage familiarity. An example table to record data for this test is provided in Table 3.4.

Table 3.4: Data collection for observing speeds between Autocorrect and familiarity levels

	Personal vs. Unfamiliar phone keyboard							
	Passage 1		Passage 2		Passage 3		Passage 4	
	Word count: 55. Personal w/ Auto. first		*Word count: 55. Personal w/o Auto first*		*Word count: 58. Unfamiliar first*		*Word count: 57. Personal w/ Auto first*	
Autocorrect	Personal	Unfamiliar	Personal	Unfamiliar	Personal	Unfamiliar	Personal	Unfamiliar
Disabled	102.7		117.01		105.39		120.87	
Enabled	104.01	128.63	96.07	120.84	103.72	125.3	108.6	130.03

"Personal" indicates the participant's personal mobile phone. "Unfamiliar" indicates the Droid Razr M, a phone that the participant is unfamiliar with in regards to typing.

3.2.2 Speed by Familiarity of Laptop

Tests 2 and 6 provided the participant with four passages varying from 58, 58, 59, and 60 words in length. The passages are provided in Appendix B. The participant was asked to type each passage on both their personal laptop keyboard and on the provided AmazonBasics keyboard, and the time to perfectly transcribe each passage was recorded in seconds. The passages were repeated between both keyboard types to keep the word count and level of word complexity constant between trials. Two passages were written first on the participant's personal keyboard then the unfamiliar keyboard, and the other two passages were written first on the unfamiliar keyboard then the participant's personal keyboard. The table utilized for data collection is shown in Table 3.5 and has been filled with another participant's trial results. To mitigate the impact of passage familiarity on the typing speed, other test types were included before the participant was asked to transcribe the same passage again.

Table 3.5: Data collection table for testing laptop keyboard familiarity effects

	Personal vs. Unfamiliar laptop keyboard							
	Passage 1		Passage 2		Passage 3		Passage 4	
	Word count: 58. Personal first.[1]		*Word count: 58. Unfamiliar first*		*Word count: 60. Personal first*		*Word count: 59. Unfamiliar first*	
	Personal	Unfamiliar	Personal	Unfamiliar	Personal	Unfamiliar	Personal	Unfamiliar
Time (seconds)	65.1	68.43	65.96	70.77	63.42	61.87	97.77	80.13

[1] This cell provides specifics on the passage that is being transcribed during this trial. The first line provides the word count of the passage and the second line indicates which keyboard would be used during the participant's first transcription of that passage.

3.2.3 Speed, Accuracy, and Mistake Type by Testing Condition on Personal Laptop

Test 3 was completed on each participant's personal laptop. During this test, the participant was asked to complete a 2- to 7-line typing test on keyhero.com. After the participant transcribed the passage, the typing test displayed the participant's average words per minute as well as the typing accuracy and type of errors performed during the test, which were colored for visual aid. The types of errors are as follows:

Bad case (pink): Indicates that the letter was mistakenly capitalized when expected lowercase, or the opposite. For example, typing "the" instead of "The" at the start of a sentence.

Bad ordering (purple): Indicates that a letter was typed out of order. For example, typing "thoery" instead of "theory".

Doublet (yellow): Indicates that a letter was mistakenly typed twice. For example, typing "heree" instead of "here".

Neglect (red): Indicates that a mistake was not corrected by the typist. For example, leaving a misspelling in the passage and continuing on without ever fixing it.

Misspelling (orange): Indicates that the participant added the incorrect letter. For example, typing "ribben" instead of "ribbon".

Punctuation (orange): Indicates that the participant neglected to add or incorrectly added punctuation. For example, typing "first and" instead of "first, and".

Participants were asked to complete twelve conditioned typing tests on keyhero.com using their personal laptop. The conditions were as follows:

Condition 1: Comfortable speed, maintaining accuracy. The instructions to the subject were to type as if they were typing a document, where accuracy should be maintained, errors should be fixed, and typing tempo should remain natural to the participant.

Condition 2: Highest possible word count. The individual was asked to type as fast as possible, neglecting accuracy or errors. The words per minute penalty naturally applied by keyhero.com for inaccuracy was added to the average speed for the trial to guarantee that an unpenalized word count was recorded.

Condition 3: No backspace. This condition imposed that the "Backspace" or "Delete" key on the laptop's keyboard could not be used. Participants were notified that, if the "Backspace" or "Delete" key was pressed, the trial would be restarted.

Conditions were rotated in turn from Condition 1 to Condition 2 to Condition 3, then the set of three conditioned trials were repeated twice more for a total of nine trials. The results were reported in an table that tracked the average speed for the entire trial, as well as the count for each individual mistake type. The table utilized for data collection is shown in Table 3.6 and has been filled with one participant's trial results.

Table 3.6: Data collection table for personal laptop imposed condition test

	Personal laptop											
	Comfortable speed, maintaining accuracy				As fast as possible, get high word count				No backspace allowed			
	Trial 1	Trial 2	Trial 3	Avg.[1]	Trial 1	Trial 2	Trial 3	Avg.	Trial 1	Trial 2	Trial 3	Avg.
Average speed (W.P.M.[2])	51.35	58.01	63.17	57.51	53.28	63.16	65.90	60.78	53.58	54.73	55.81	54.71
Mistakes												
Advertised accuracy	69.42	65.93	60.77	65.37	44.31	50.33	53.88	49.51	73.68	46.78	75.78	65.41
Capitalization (pink)	2	0	0	0.67	0	1	0	0.33	0	0	0	0
Bad ordering (purple)	2	0	1	1	0	0	0	0	0	0	0	0
Doublet (yellow)	0	0	0	0	0	0	0	0	0	0	0	0
Neglect (red)	3	5	8	5.33	11	7	2	6.67	3	9	3	4.67
Misspell (orange)	9	5	4	6	2	3	2	2.33	0	0	0	0
Punctuation (orange)	0	0	0	0	0	0	1	0.33	0	0	0	0

[1] Average of the three trials, rounded to the nearest hundredth. [2] words per minute

3.2.4 Speed, Accuracy, and Mistake Type by Device Type

For Test 5, the participant downloaded the mobile phone typing test application TapTyping and used the "Speed Test" function, which provides the participant with a short passage to transcribe of approximately 30 words in length. Once the passage had been transcribed by the participant, the application displayed the participant's typing speed in words per minute, percent accuracy, time to complete the trial, and "Instant Replay" function. The speed (in words per minute) and time to complete the trial were recorded, as well as the specific error types found through watching the Instant Replay. The specific error types are as follows:

Space: Participant either added an incorrectly-placed space between words or neglected to input a required space. For example, typing "to theleft" instead of "to the left".

Spelling: Participant added the incorrect letter. For example, typing "ribben" instead of "ribbon".

Punctuation: Participant neglected to add or incorrectly added punctuation. For example, typing "first and" instead of "first, and".

Other: Any extraneous error was categorized as "Other" and described in this label.

The table utilized for data collection is shown in Table 3.7 and has been filled with another participant's trial results.

Table 3.7: Data collection table for observing mistake types on personal phone

	Personal phone			
	Comfortable speed, maintaining accuracy			
	Trial 1	Trial 2	Trial 3	Average
Time (seconds)	55	54	48	52.33
Average speed (WPM)	26	25	32	27.67
Mistakes				
Space	0	1	0	0.33
Spelling	5	0	0	1.67
Punctuation	0	0	0	0
Autocorrected word	0	0	0	0
Other	0	0	0	0

Three trials were conducted using TapTyping, a mobile phone application, and the occurrence count for each specific mistake type were recorded in the according cell. Average values have are rounded to the nearest hundredth.

In addition to the error category, the specific keys that produced the error were collected. A table of the intended key, hit key, and frequency was populated to observe which keys are more frequently mistyped. The table that was filled during these trials, along with the table shown in Table 3.7, in shown in Table 3.8 with an example data set.

Table 3.8: Data collection table for recording specific letter mistypes on personal phone

Troublesome Keys		
Intended	Hit	Frequency
i	o	1
e	c	1
u	i	2

The rows of this table were filled in with the mistypes executed by the participant when typing on the TapTyping application. The "Intended" column records the key that the TapTyping passage expected the participant to hit, which is the next letter in the word or phrase that the participant is typing. The "Hit" column records the key that the participant hit, when the key differed from the intended key. The "Frequency" column tracks the number of times that a specific pair of "Intended" and "Hit" keys occurred for that participant throughout the three trials. The table was shortened or extended to fit the number of mistypes unique to that participant.

3.3 Data Analysis

Once the data were acquired, statistical analysis was conducted between trials and subgroups to determine trends and evaluate statistical significance. Statistical significance was evaluated with a confidence level of 95% (p-value < 0.05). Each participant's difference in typing speeds was normalized by their original speed in order to equalize the weight of each difference in the larger analysis. Trends were investigated between independent variables such as Autocorrection level, sex, and device type by separating the data by variable and investigating the statistical significance of change between variables. Statistical significance was determined through paired and unpaired t-tests between participant typing speeds, accuracies, and mistake types.

4 Results and Discussion

Each participant's trial results were recorded and analyzed to observe dependences of typing speed and accuracy on device familiarity, device type, and correction style used. The results have been separated into the following sections: Laptop Trial Results, Phone Trial Results, and Laptop vs. Phone Comparison Results.

4.1 Laptop Trial Results

Laptop trials were conducted through the transcription of four passages on both familiar and unfamiliar keyboards (as described in Section 3.2.2) and completion of 3 typing tests on keyhero.com, each repeated under three conditions: comfortable speed while maintaining accuracy, attempting to achieve the highest possible word count, and prohibiting the use of backspace. The results from passage transcriptions concluded that each participant tended to either decrease in typing speed or maintain a consistent typing speed when typing on an unfamiliar laptop. When the results from all participants were grouped together, the typing speed on the unfamiliar laptop was statistically significantly slower than on the familiar laptop, with speed ratio of $(96 \pm 2)\%$.

The results were then grouped to compare between participants' familiar laptop models, where the results show that typing on an unfamiliar keyboard that is less similar to a participant's personal keyboard will cause the participant to decrease in typing speed more significantly than a participant who is accustomed to typing one similar to the unfamiliar keyboard ($(94.5 \pm 3.5)\%$ for less similar laptops and $(97.3 \pm 2.4)\%$ for most similar laptops). Attempting to type at a faster speed did not affect the typing speed but increased the frequency of neglect errors by a factor of 20, and prohibiting the use of backspace caused participants to type 10% slower than their comfortable speeds on average but decreased the frequency of certain errors such as capitalization, bad ordering, misspelling, and punctuation. Misspellings and bad ordering are consistently the most frequent error types while typing on a laptop and account for approximately 80% of errors. The following sections describe these results in more detail.

4.1.1 General Results on Laptop Keyboard Familiarity

The laptop passage transcription times between personal and unfamiliar laptop keyboards were compared to observe the effects of device familiarity on typing speed, using the results from the tests described in Test 2 of Section 3.2 . The transcription times were compared between the two keyboards for each participant to see how their typing speed changed. Figure 4.1 shows participants' unfamiliar laptop typing speeds as a function of familiar laptop typing speeds, averaged for each participant and each passage. The four points for each participant are color-coded by participant.

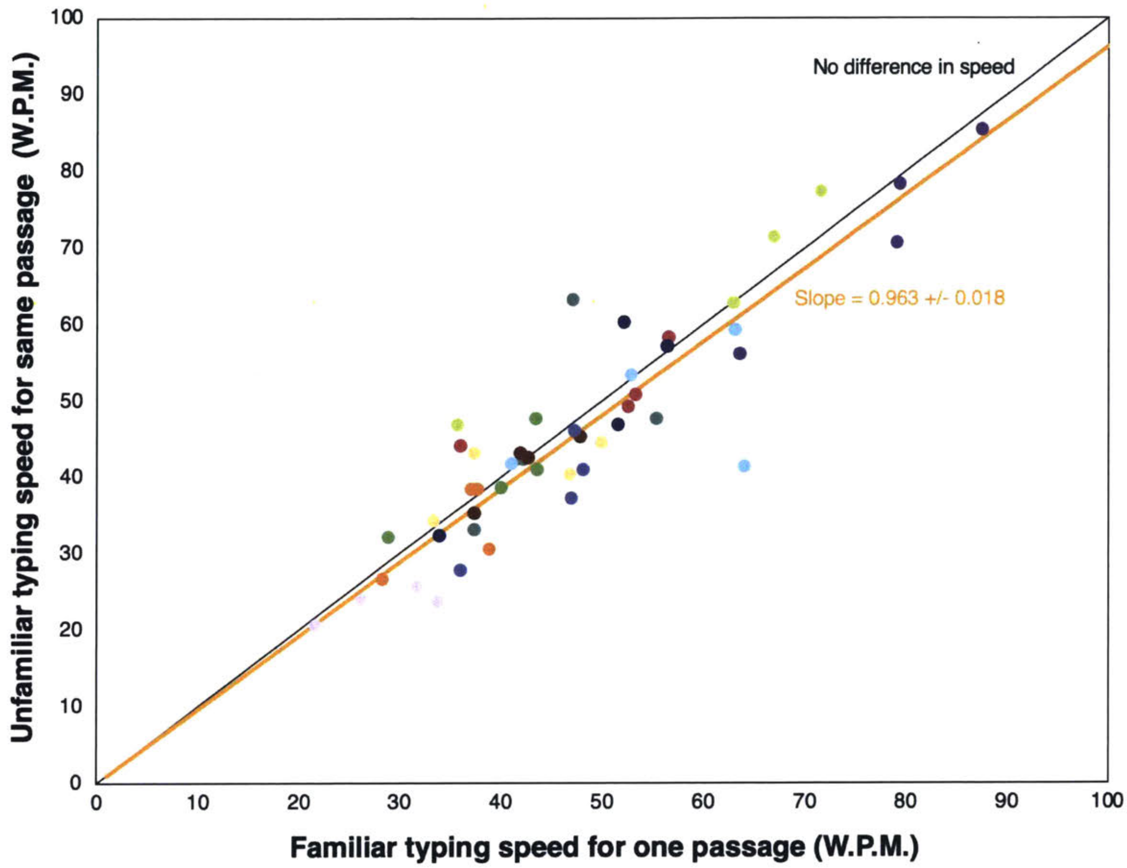

Figure 4.1: Familiar laptop typing speed to unfamiliar laptop typing speed. Each point is one trial for one passage by a single participant, color-coded by participant. Points below the line indicate that the participant's typing speed was faster on the familiar laptop keyboard. It is apparent that more of the points fall below the line, with 30 of the 48 transcribed passages (62.5%) resulting in slower typing speeds on the unfamiliar keyboard than on the familiar keyboard. The orange line shows the data's trend, following $y = (0.963 \pm 0.018)x$. All participants in aggregate typed more slowly on the unfamiliar laptop with speed 94% - 98% that of their speed on their own laptop.

There was a slight tendency for participants to type slower on the unfamiliar keyboard, with 30 of the 48 transcribed passages (62.5%) having slower typing speeds on the unfamiliar keyboard than on the familiar keyboard, as indicated by points lying below the $y = x$ line (in black).

A proportional fit of the data yields the line $y = (0.96 \pm 0.02)x$ (shown in orange in Figure 4.1), where the uncertainty is specified with 95% confidence. Because the line's slope does not include 1.0 in the confidence interval, the difference between the fit line and the line $y = x$ (no speed difference) is statistically significant. Therefore, data from all individuals tested indicates that they typed more slowly on the unfamiliar laptop with speed $(96 \pm 2)\%$ that of their speed on their own laptop. Individuals who type at a higher speed on their familiar laptop keyboard will have a larger absolute decrease in their typing speed (in W.P.M.).

The data were then normalized by the participant's typing speed on their familiar keyboard to observe the percent difference in typing speed for each passage and individual, as displayed in Figure 4.2. The color coding in figures 4.1 and 4.2 are the same for each participant.

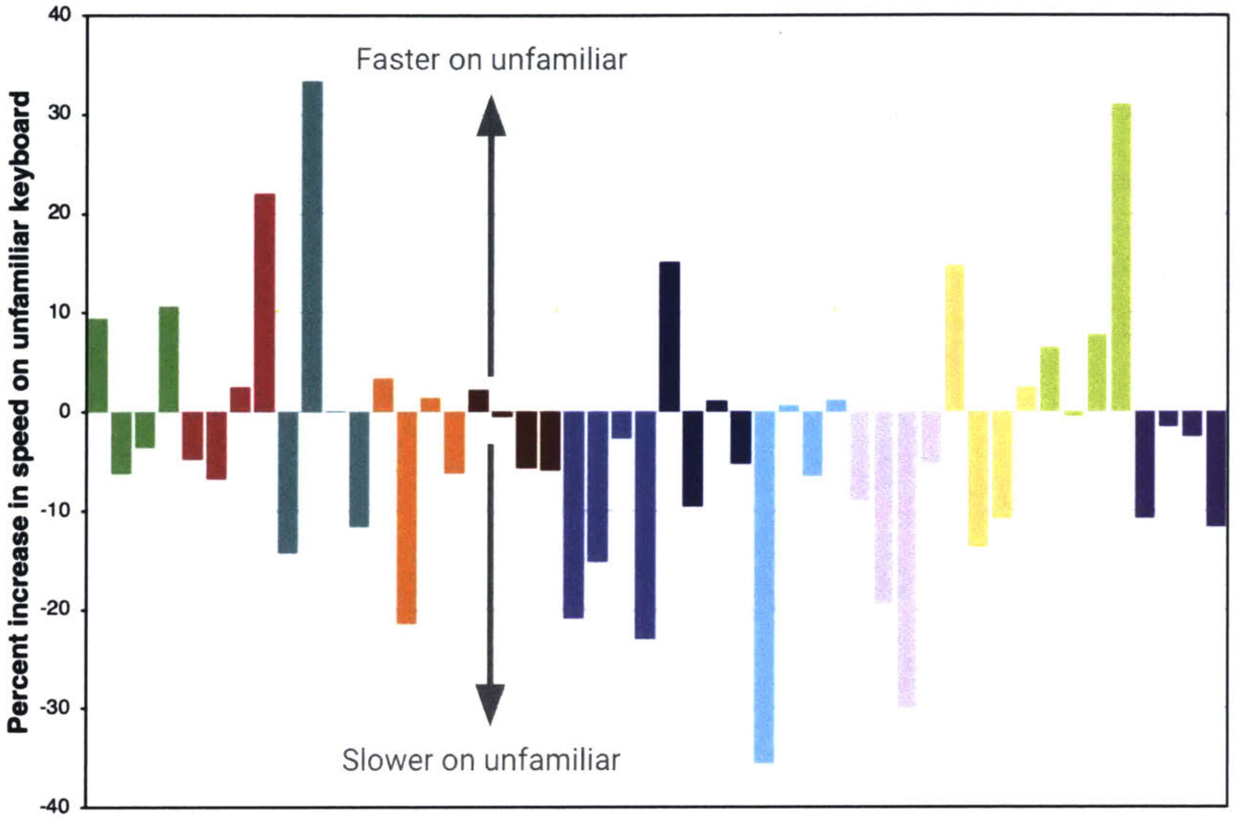

Figure 4.2: Percent increase in typing speeds between typing on familiar and unfamiliar laptop keyboards, colored by participant. The four bars for each participant display the four passage results. Bars below the zero line indicate a negative percent change, or decrease in typing speed, where the participant typed slower on the unfamiliar keyboard than on the familiar keyboard.

Figure 4.2 shows that a majority of the percent increases are negative (31 out of the 48, or 65% of trials), indicating that participants are more likely to decrease in speed when typing on an unfamiliar laptop keyboard. By categorizing percent changes of >10% as "large changes", the data show that large changes are seen in nearly half of the trials that decreased in speed and one third of the trials that increased in speed. Most of the positive speed increases are very slight increases below 5%, whereas negative speed increases are more frequently between -5% and -15%. This indicates that the more frequent and significant changes in speed are speed decreases, and trials that increased in speed most frequently saw either large (>10%) or small (<5%) percent changes in speed.

The percent changes in speed shown in Figure 4.2 were then categorized into three categories: slower (indicating that the individual's typing speed on an unfamiliar keyboard was < 97.5% of the familiar typing speed), unchanged (unfamiliar typing speed was within 2.5% of the familiar typing speed), and faster (indicating that the individual's typing speed on an unfamiliar keyboard was > 102.5% of the familiar typing speed. The number of trials labeled as slower, unchanged, or faster along with average speeds for each category are shown in Table 4.1.

Table 4.1: Comparison of laptop speeds between familiar and unfamiliar laptop keyboards

Speed category	Numerical condition for category	Number of trials qualifying in category	Average speed (% of familiar speed)
Slower	$V_{unfam} < 97.5\%V_{fam}$	19	92.5 ± 2.0%
Unchanged	$97.5\%V_{fam} < V_{unfam} < 102.5\%V_{fam}$	20	99.51 ± 0.56%
Faster	$V_{unfam} > 102.5\%V_{fam}$	9	107.3 ± 2.6%

Approximately 80% of trials fell into the slower or unchanged speed categories, indicating that only 1 in 5 trials were typed faster on an unfamiliar keyboard. The average speeds while typing on an unfamiliar laptop, shown as a percentage of the participant's familiar speed for that passage, validate that the speeds for the unchanged trials are indeed unchanged (as the uncertainty for the average speed overlaps 100%, which represents no speed change). The slower and unchanged average speeds are about evenly distanced from 100%, with slower being 7.5% below 100% and faster being 7.3% above 100%.

In order to more readily observe the distribution of percent differences for all trials, the data were arranged in a histogram and are shown in Figure 4.3.

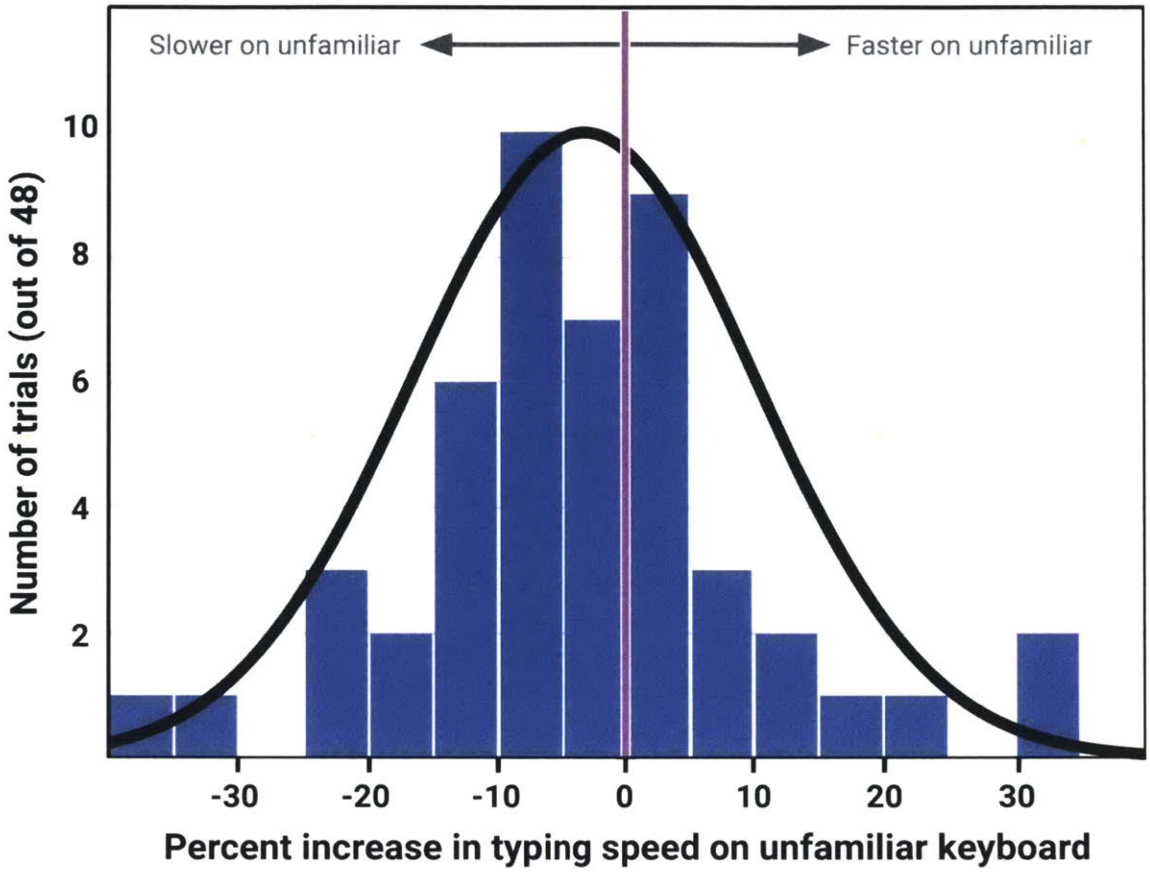

Figure 4.3: Histogram of the percent differences in typing speeds on laptop keyboards. Zero along the x-axis (magenta line) indicates that there was no difference in typing speed between familiar and unfamiliar keyboards. Mean value of the normal distribution is (-3.3 ± 1.9)% and the standard deviation is (13.4 ± 1.4)%.

Figure 4.3 visually demonstrates the aforementioned tendency for typing speed to decrease when typing on an unfamiliar laptop keyboard. Fitting an normal distribution to Figure 4.3 results in a mean value of -3.3% and a standard deviation of 13.4%. The normal distribution's shift to the left reiterates that speed decreases are most frequent when using the unfamiliar AmazonBasics keyboard.

The percent changes shown in Figure 4.2 were then analyzed by participant. Figure 4.4 shows the average percent change for each participant, as well as the 95% confidence interval for each participant's set of four passages.

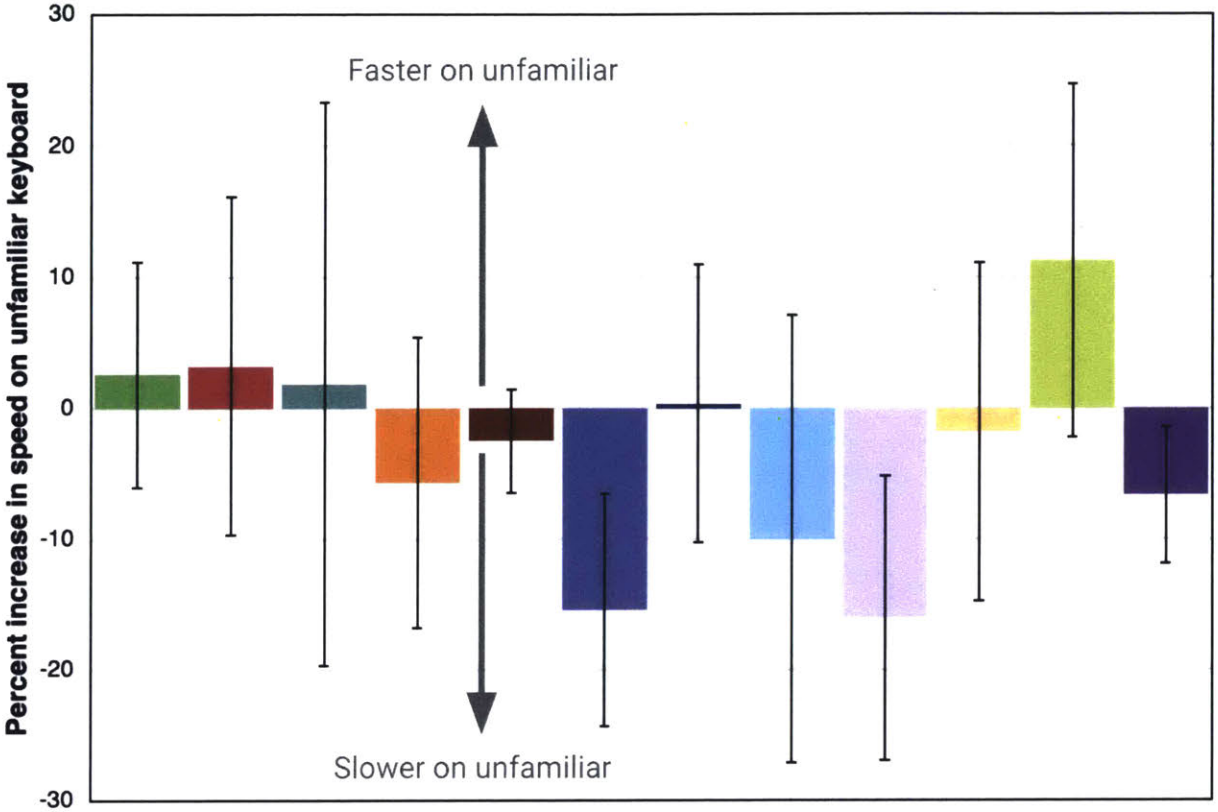

Figure 4.4: Percent increase in typing speeds on unfamiliar laptop from familiar laptop speed, averaged and colored by participant.

As seen in Figure 4.4, only three of the twelve participants saw statistically significant changes in typing speed, all of whom displayed decreased in typing speed on the unfamiliar laptop to speeds ranging from 84% to 93% of the familiar laptop speeds. The other nine participants, though having nonzero average percent changes in typing speed, had 95% confidence intervals that overlapped with zero. The inclusion of zero in the 95% confidence ranges disallows conclusions from being easily drawn regarding how laptop keyboard familiarity impacts typing speed individually for each participant, although as shown in Fig 4.1, when all participants were considered together, there was a statistically significant decrease in typing speed on the unfamiliar keyboard.

4.1.2 *Effects of Device Familiarity on Laptop Typing Speed*

As discussed in Section 2.4 of the Background, Dell keyboards are most similar to the AmazonBasics in their key dimensions and keyboard materials. MacBook Pro scissor mechanisms are the second-most similar, and MacBook Pro butterfly mechanisms are the least similar. The data presented in Figure 4.1 has now been recolored to display the typing speeds for each of the three keyboard models to further analyze the effects of keyboard familiarity on laptop typing speed.

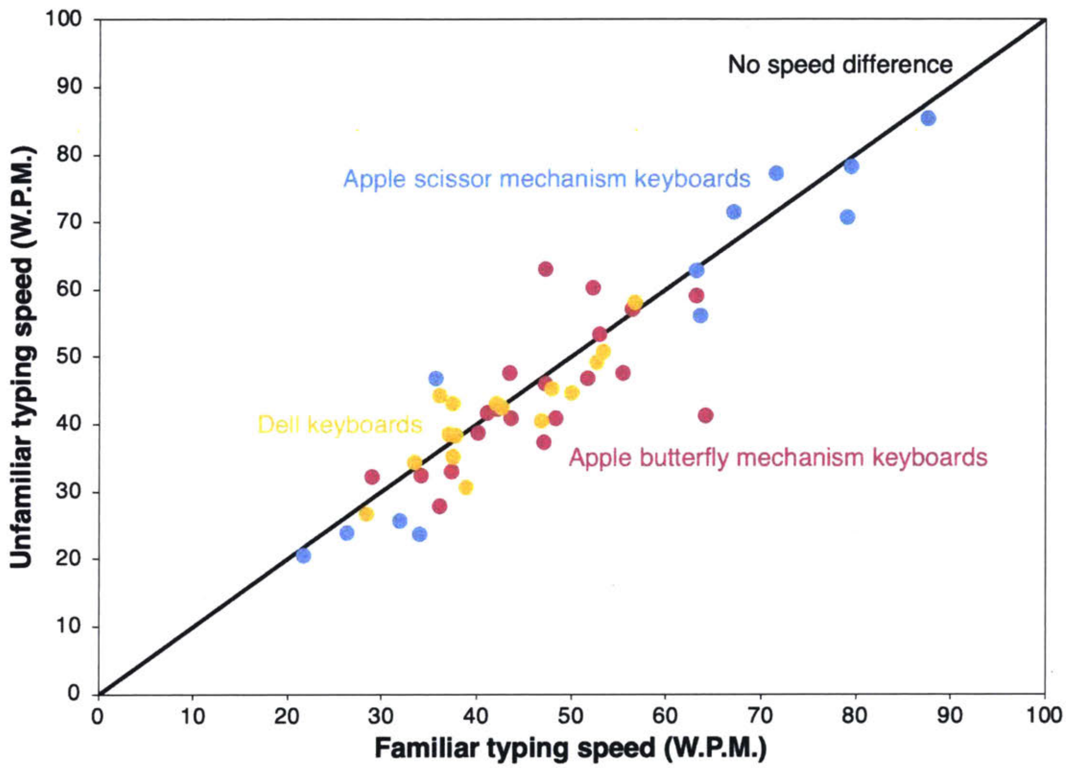

Figure 4.5: Familiar laptop typing speed to unfamiliar laptop typing speed, colored by laptop model. Each point is one trial for one passage by a single participant. Black line y = x represents no difference in typing speed. Proportional fit lines for each keyboard model are colored to match the individual data points.

As seen in Figure 4.5, the trials results as a whole tend to follow the diagonal y = x line that indicates no change in speed between familiar and unfamiliar laptop keyboards. Initial observations by keyboard model also shown no immediate and obvious trends, as the data points for each keyboard model are spread and well-mixed with the data representing the other models.

All three fit lines for the three keyboard models fall below the line y = x (no speed difference) with the following best-fit equations and 95% confidence intervals of the best-fit slope. The number of subjects tested for each model is indicated below:

Apple butterfly mechanism:	$y = (0.945 \pm 0.035)x$, slope = (0.910, 0.980) (5 subjects)
Dell:	$y = (0.973 \pm 0.024)x$, slope = (0.949, 0.997) (4 subjects)
Apple scissor mechanism:	$y = (0.976 \pm 0.031)x$, slope = (0.945, 1.007) (3 subjects)

The uncertainty bounds for all three slopes overlap, indicating that the differences in typing speed on the unfamiliar laptop do not have a statistically significant dependence on style of familiar keyboard. However, the best-fit slopes for Dell and Apple butterfly mechanism keyboards do not include 1.0 in the uncertainty interval and therefore users of these keyboards typed statistically significantly more slowly on the unfamiliar keyboard than on their own laptop.t. The slope for the Apple butterfly mechanism keyboards is the lowest, which is interesting because, as explained in Section 2.4, this keyboard is mechanically the least similar to the unfamiliar AmazonBasics keyboard. Interestingly, Dell laptop users exhibited very slightly slower typing speed on the AmazonBasics keyboard, even though their familiar keyboard had the most mechanical similarity to the unfamiliar keyboard, In contrast, the best-fit slope for the Apple scissor mechanism keyboards does include 1.0 in the uncertainty interval and therefore users of this laptop exhibited no statistically significant difference in typing speed on the unfamiliar laptop.

The percent differences were then arranged and sorted by keyboard model to observe the frequency of each percent difference range. The percent differences for each of the four passages by the twelve participants are shown in Figure 4.6.

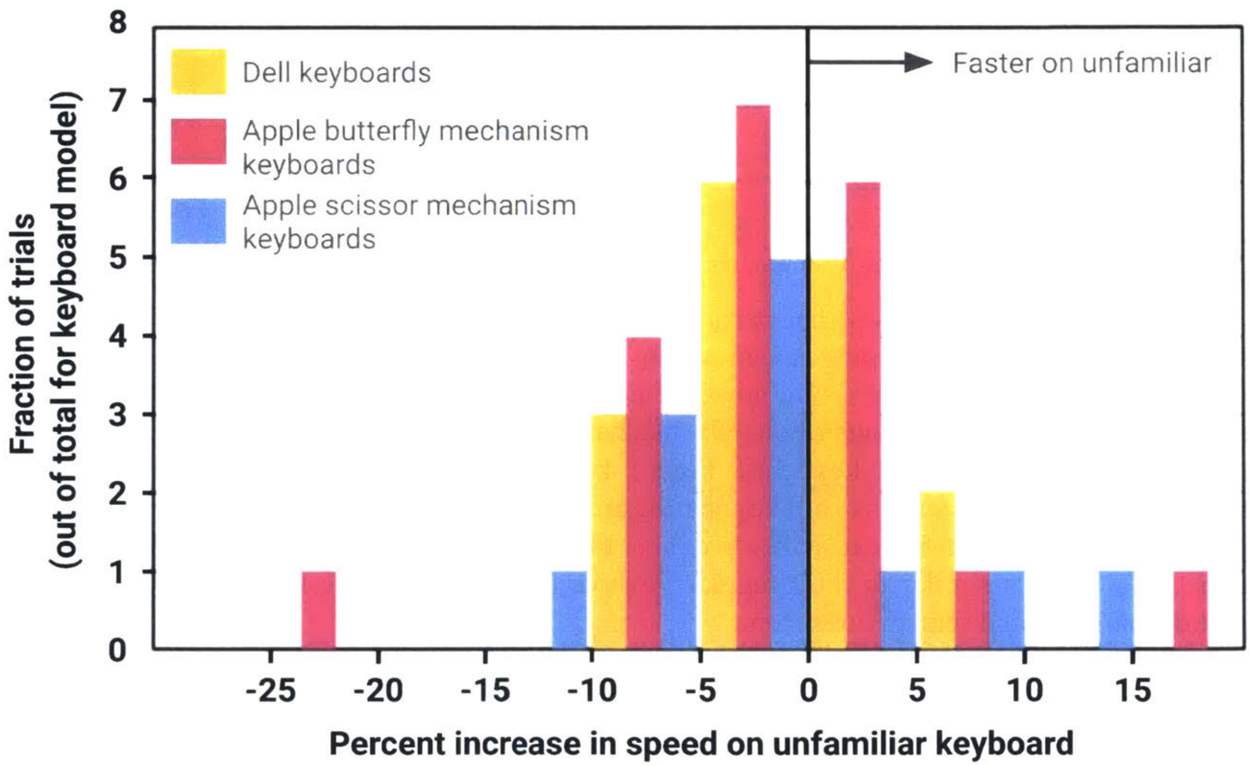

Figure 4.6: Percent increase in typing speeds between typing on familiar and unfamiliar laptop keyboards, colored by keyboard model.

The overlaid histograms in Figure 4.6 show that each of the three keyboard models experience similar speed increase distributions. All distributions appear to be Gaussian and centered just left of the vertical line at x = 0 (no speed increase), indicating that it is more common for typing speeds to decrease across each all three keyboard models.

As done in the previous section, each trial was categorized as slower (< 97.5% of familiar speed), unchanged (within 2.5% of familiar speed), and faster (>102.5% of familiar speed). The fraction of trials for specific keyboard models who typed at slower, unchanged, and faster typing speeds are shown in Figure 4.7, separated by keyboard model.

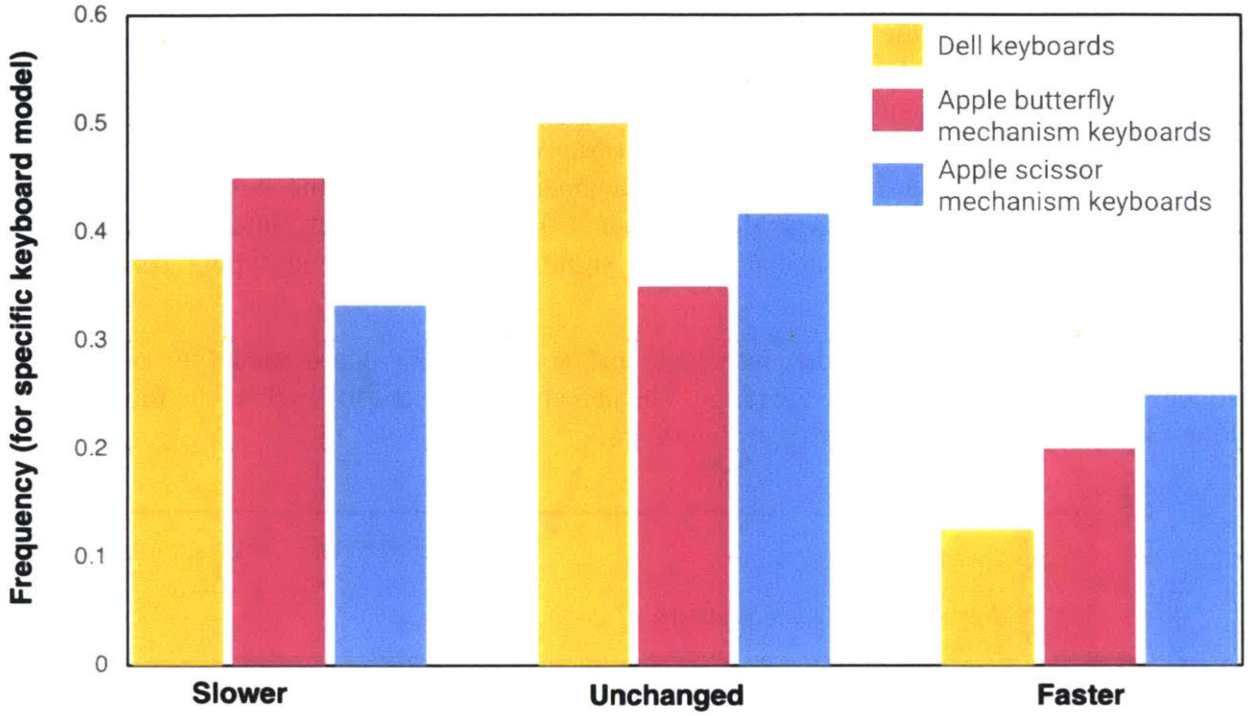

Figure 4.7: Percentage of slower, unchanged, and faster typists by laptop keyboard type.

As expected, Figure 4.7 shows that participants more frequently slowed or remained the same rather than quickened in typing speed when typing on an unfamiliar keyboard. Across all keyboard models, typing faster is the lowest frequency category. Individuals typing on the least similar keyboard model (Apple's butterfly mechanism keyboards) are most likely to type at a slower rate on the unfamiliar keyboard. Figure 4.7 also shows that participants who type on a familiar keyboard type, such as Dell keyboards, are most likely to remain unaffected from typing on an unfamiliar keyboard because they are most likely to have unchanged speeds. This is logical as the unfamiliar is similar to their regular keyboard and therefore the feeling of typing on the two keyboards should remain consistent.

To observe the difference in percent changes in speed by keyboard model, were averaged by keyboard model and shown in Figure 4.8.

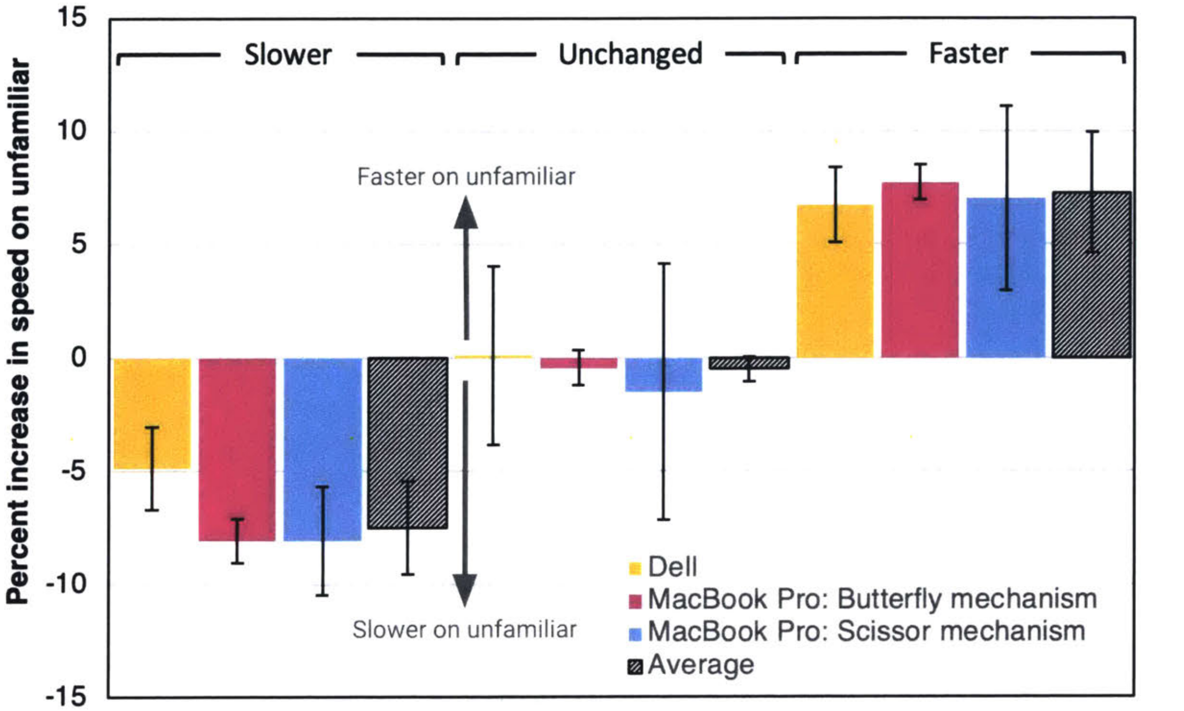

Figure 4.8: Average percent increase in speed by laptop keyboard type, compared to average percent change. Striped grey represents the average percent change in speed calculated in Section 4.1.1.

The percent changes per each typing change group (slower, unchanged, and faster) appear relatively consistent and close to that category's average across keyboard models within the group, with the exception of slower Dell users. In the unchanged category, the percent changes for all three laptop models have error bars that overlap zero, indicating that there is no statistically significant change in typing speed for any keyboard model. All four bars for both the slower and faster categories are statistically significant and do not overlap zero.

In summary, participants who regularly typed on Dell keyboards (considered to be the most similar to the unfamiliar AmazonBasics keyboard) were most likely to have an unchanged typing speed on the unfamiliar keyboard (50% of the subjects with an unchanged typing frequency were regular Dell keyboard typists).

Unsurprisingly, typists who regularly use the MacBook Pro butterfly mechanism keyboards (which are regarded as the least similar to the unfamiliar AmazonBasics keyboard) were most frequently affected by the unfamiliar laptop keyboard, as they are shown to be the most frequent keyboard model to have a slower typing speed when typing on the unfamiliar keyboard. Slower and unchanged typing speeds for butterfly keyboard users are much more frequent (80% of typing instances) than faster speeds (20% of typing instances).

In summary, the results do not conflict with expectations that users of the most similar keyboard (Dell) exhibit less change in typing speed on the AmazonBasics keyboard, while users of the least similar keyboard (MacBook Pro post-2016 butterfly keyboard) exhibited the largest decrease in typing speed on the AmazonBasics keyboard. However, the large uncertainties, most likely due to the small number of subjects tested for each keyboard, do not allow these observations to be stated with 95% confidence.

4.1.3 Effect of Testing Condition on Laptop Typing Speed

Each participant completed four typing tests for three announced conditions on keyhero.com: comfortable speed and maintaining accuracy, highest possible word count, and prohibiting the use of "backspace" or "delete". The participant's typing speed, accuracy, and specific mistake types were recorded. The typing speeds for each participant across the three conditions are shown in Figure 4.9.

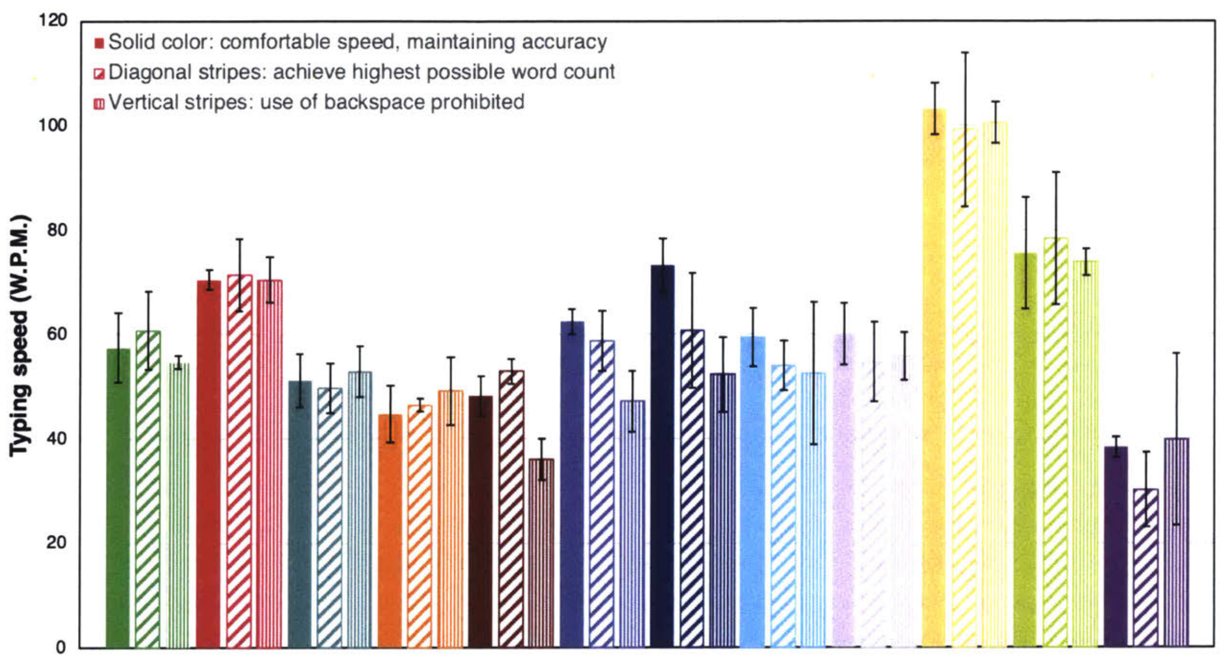

Figure 4.9: Comparing typing speeds between testing conditions, colored by participant. Bars show the average typing speed over three trials at the specific condition that are differentiated by three distinct patterns.

As shown in Figure 4.9, there is no significant change in speed for all participants even when trying to achieve the highest word count. Although individual participants see changes in typing speed between trials, there is no consistent trend across all participants. The average speeds for the second two conditions (highest possible word count and prohibiting backspace) were compared against the first speed (comfortable typing, maintaining accuracy). The percent difference in typing speed between comfortable and fast typing (black bars) and between comfortable typing and typing without backspace (grey bars) are shown in Figure 4.10.

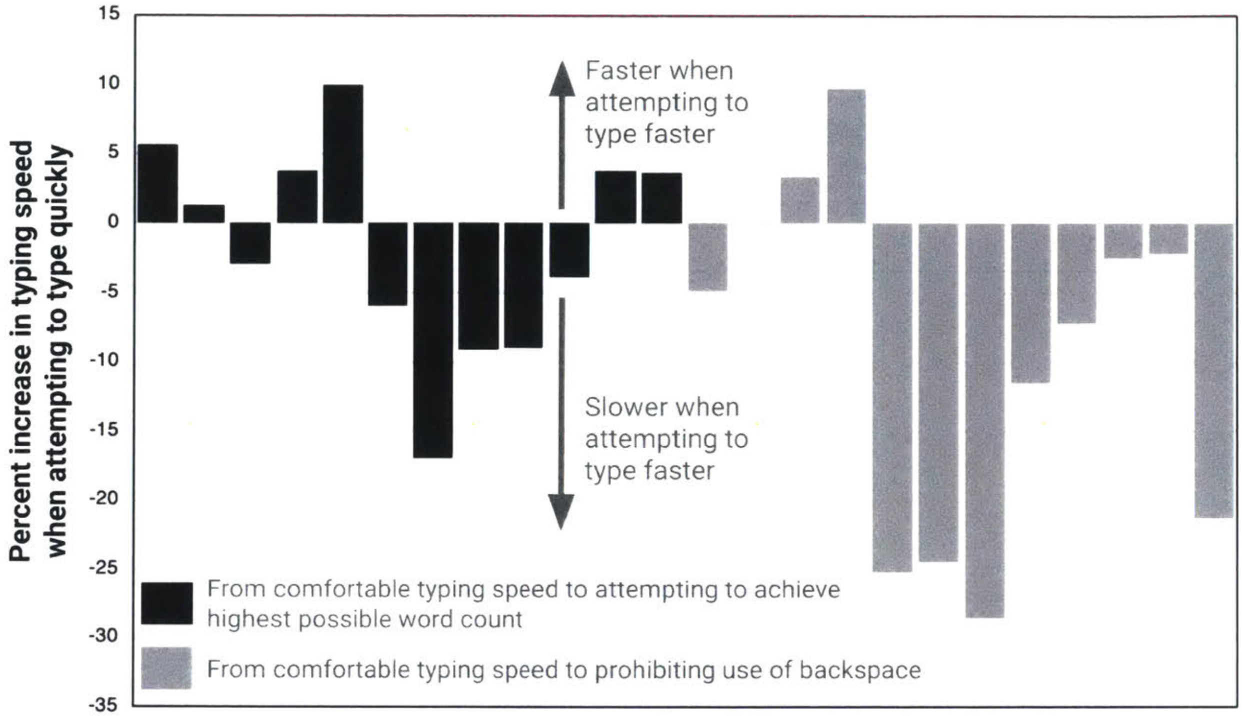

Figure 4.10: Percent increase in laptop typing speeds between conditions.

Figure 4.10 shows that participants are more likely to decrease in typing speed when they are prohibited from using the backspace key. Prohibiting participants from using certain keys (here, "Backspace" or "Delete") did significantly change the typists' speeds. When unable to use the backspace key, the typing speed decreased by approximately 10%, indicating that removing the participants' ability to use a traditionally-utilized mistake-eraser caused the participants to type more slowly. This conclusion was rendered statistically significant by a one-tailed t-test with a p-value of 0.0104.

When attempting to type at the highest speed possible, the changes in speed were nearly evenly split between speed increases and decreases, indicating that there is not a consistent effect and that attempting to type faster does not necessarily result in a faster typing speed. A paired one-tailed t-test showed that there is no statistically significant difference in speed between when the typist was attempting to type at a comfortable speed and attempting to type as fast as possible (with a p-value of 0.164).

4.1.4 Effects of Sex of Participant on Laptop Typing Speed

Typing speeds were compared between different demographic variables as self-identified in the participant background survey that preceded each testing session. The participants' average comfortable laptop speeds, identified in the conditional laptop speed tests and described in Section 3.2.1, were used to compare between males and females. The typing speeds for all three trials for each participant are shown in Figure 4.11.

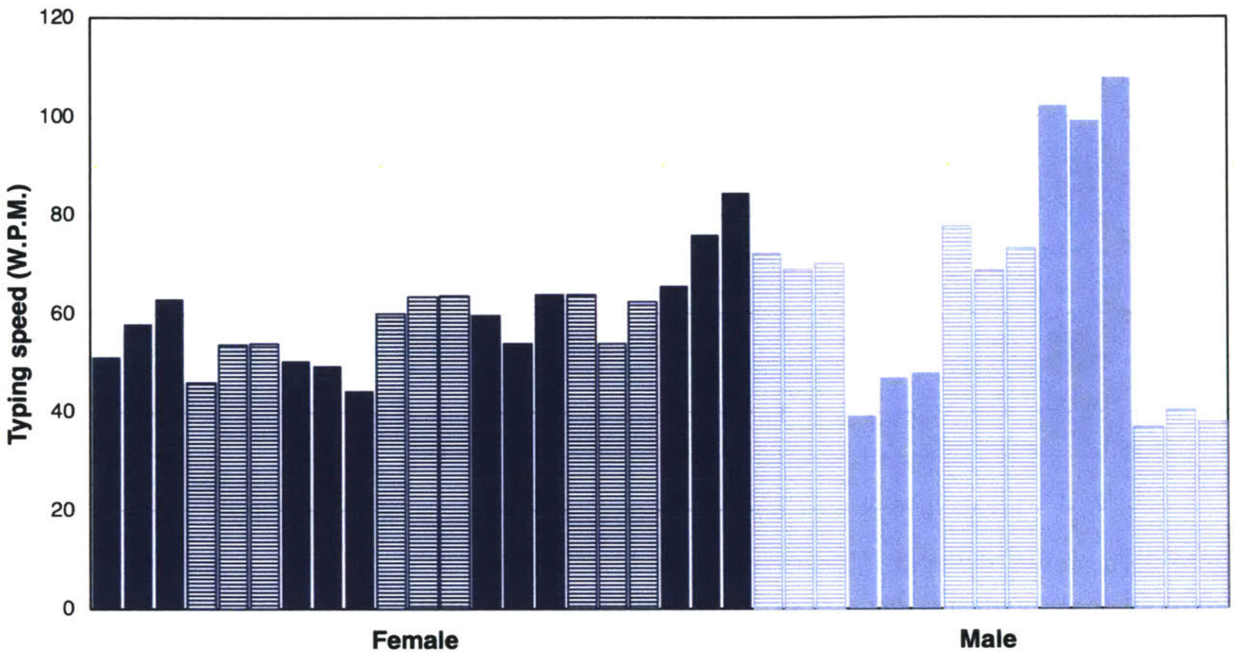

Figure 4.11: Three instances of comfortable laptop typing speed per participant, organized and colored by sex. Individual participants are distinguished with alternating filled and striped bars.

Figure 4.11 suggests that there is no immediately apparent difference between males and females in typing speed. Although the typing speeds for males exhibit a larger range of speeds, both sexes appear to settle around the same average value. The average female typing speed was 59.2 ± 4.1 words per minute. The average male typing speed was 66 ± 12 words per minute. Despite the difference in measured average typing speed, an unpaired one-tailed t-test shows that there is no statistically significant difference between the typing speeds of males and females ($p = 0.298$). These conclusions follow the prior research discussed in Section 2.3.1, where Denis LaBonty found no statistically significant relationship between finger size or participant sex and typing speed, with finger size for males generally being approximately 20% thicker and 10% longer than for females (Attwood, 2004).

4.1.5 Effects of Undergraduate Major on Laptop Typing Speed

The participants' average comfortable typing speeds on laptops were then used to compare between undergraduate majors. The typing speeds for all three trials by each participant are shown in Figure 4.12, and the average typing speed for each major is shown in Figure 4.13.

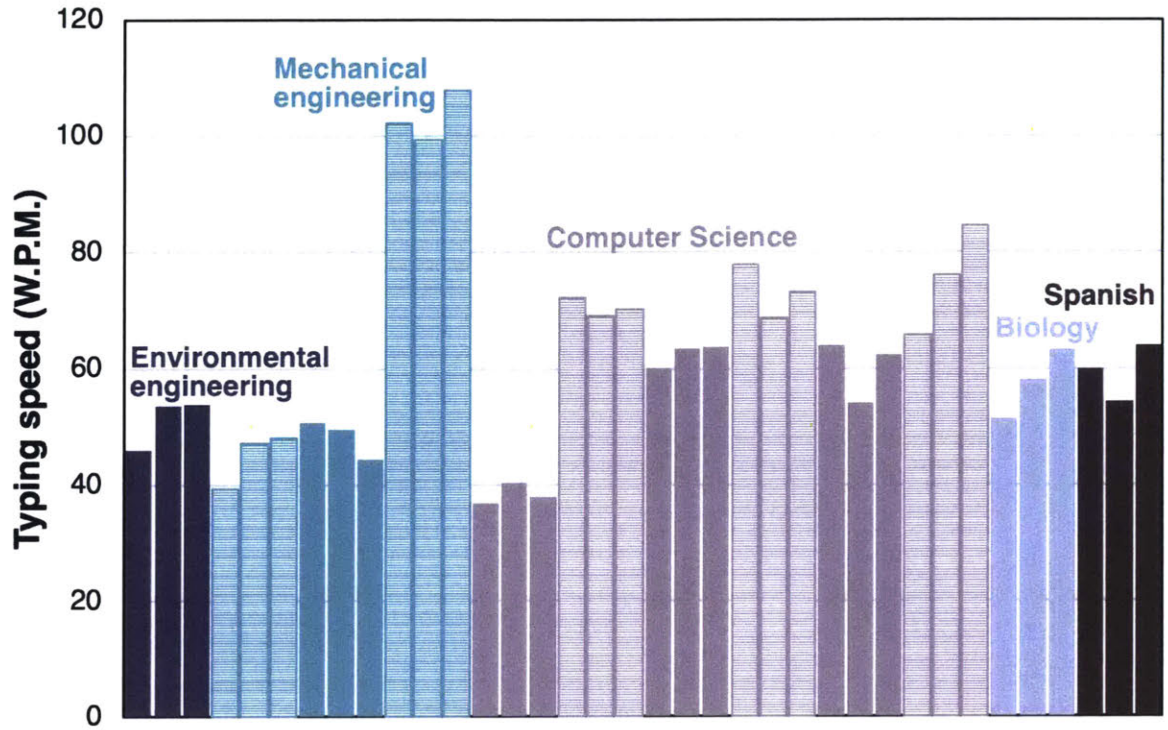

Figure 4.12: Three instances of comfortable laptop typing speed per participant, organized and colored by undergraduate major. Individual participants are distinguished with alternating filled and striped bars.

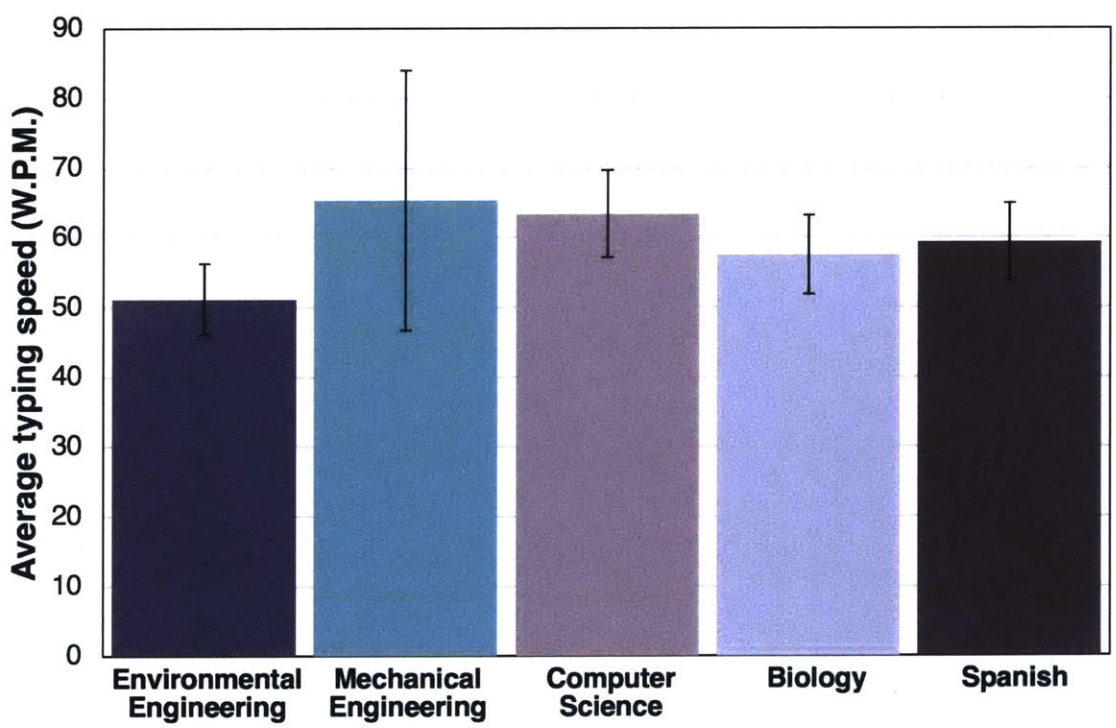

Figure 4.13: Average laptop typing speed by department. The larger error bar for Mechanical Engineering results from the single subject with average typing speed of 100 WPM, which is 20 WPM or more greater than for the other subjects

Figure 4.12 shows that typing speeds are not immediately related to the participant's undergraduate major, which is supported by the averages shown in Figure 4.13. The error bars for each major's average overlap with other majors, indicating that no statistically significant difference can be concluded. T-tests were conducted between every combination of major, utilizing the unaveraged typing speeds that are shown in Figure 4.12. The only two majors to have a statistically significant difference between them are environmental engineering and computer science ($p = 0.014$). Before making conclusions regarding the typing speed of Environmental Engineering majors, more participants should be gathered to increase the amount of data for each department.

4.1.6 Frequency of Mistake Type on Laptop Keyboards

The typing tests on keyhero.com displayed the specific category of typing error that was performed by the typist during each trial. Each participant's number of a specific error type was divided by the total number of errors performed by that individual in order to normalize the data and provide only the frequency of that error type. The frequencies of specific error types by participant when typing on their personal laptop is shown in Figure 4.14: a) through f).

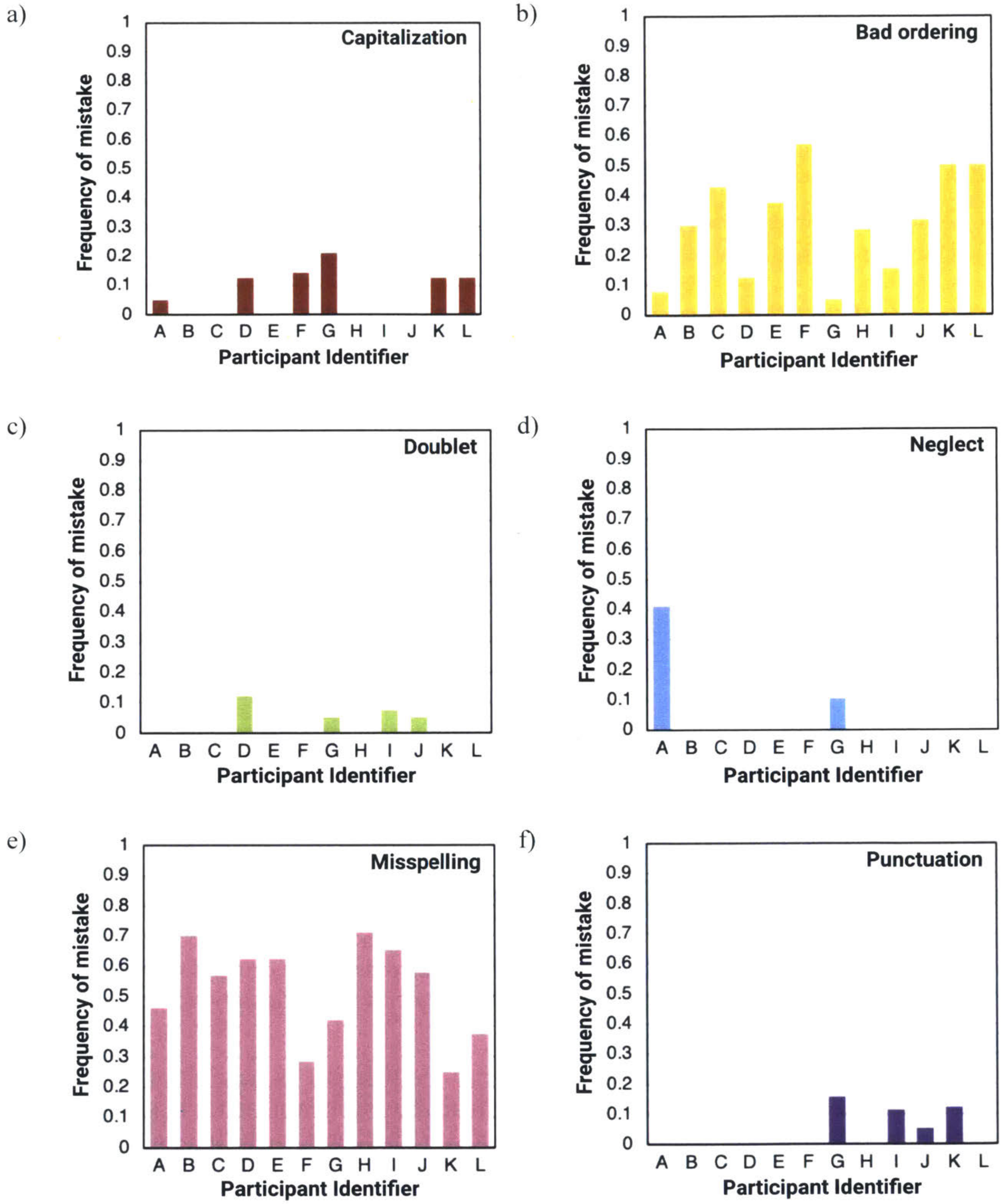

Figure 4.14: (a) Capitalization, (b) bad ordering (b), doublet (c), neglect (d), misspelling (e), and punctuation (f) mistake frequencies by participant.

Upon first glance, it is apparent that misspellings and bad ordering are the most frequent mistake types across the majority of participants, and the rest of the mistake types are often a frequency of 20%. Misspellings account for a majority of typing errors on personal laptops for nine of the twelve participants. The second most frequent mistake is bad ordering (Fig. 4.14b), where a word's correct letters are hit out of order with respect to each other. Participants F, K, and L were the only participants to not have "misspell" as the most frequent mistake and instead all had "bad ordering" as the most frequent and "misspell" as the second most frequent.

The frequencies from each individual shown in Figure 4.14 were averaged across all individuals to find the average frequency of each mistake type, which are displayed in Figure 4.15.

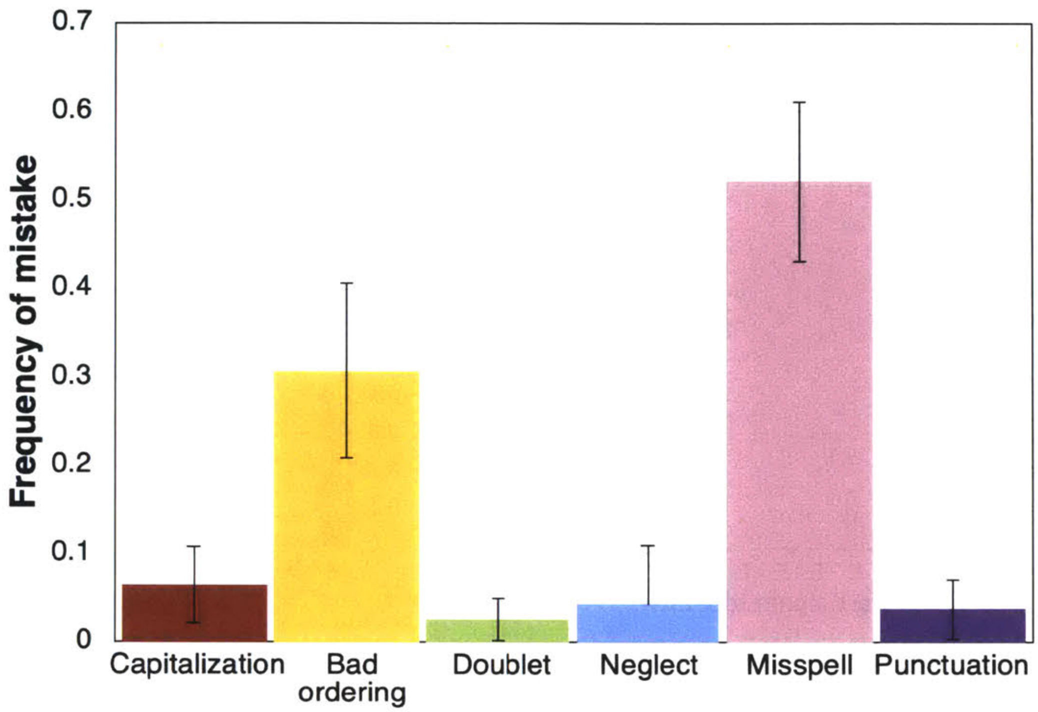

Figure 4.15: Average frequency by laptop typing mistake

Misspellings, were found to be the most frequent error type, accounting for about half of typing errors on personal laptops. The second-most frequent, bad ordering, accounts for about one third of typing errors on personal laptops. All other tabulated errors individually accounted for less than 10% of total errors.

Letters are the most frequently-occurring aspects of the passages as they make up all of the individual words, and aspects such as capitalizations and punctuation are much less frequent. For example, the paragraph above this is made up of 253 characters, including punctuation and excluding spaces. Of those characters, approximately 4.3% of the characters are punctuation and approximately 3.2% of the characters are capitalized letters. This random sample demonstrates that are many more opportunities to make a mistake when typing letters in the passage than when typing punctuation or capitalized letters.

"Bad ordering" is also a frequently-occurring mistake type and is in fact a subset of misspelling.

As described in Section 2.4.3, Apple's butterfly mechanism has led to customer dissatisfaction due to the the keys' tendencies to stick and type doublets. The results of the present study were used to compare the number of doublets typed between keyboards with and without butterfly mechanisms. The average frequencies for each participant during comfortable and fast speeds, organized into their utilized keyboard model, are shown in Figure 4.16.

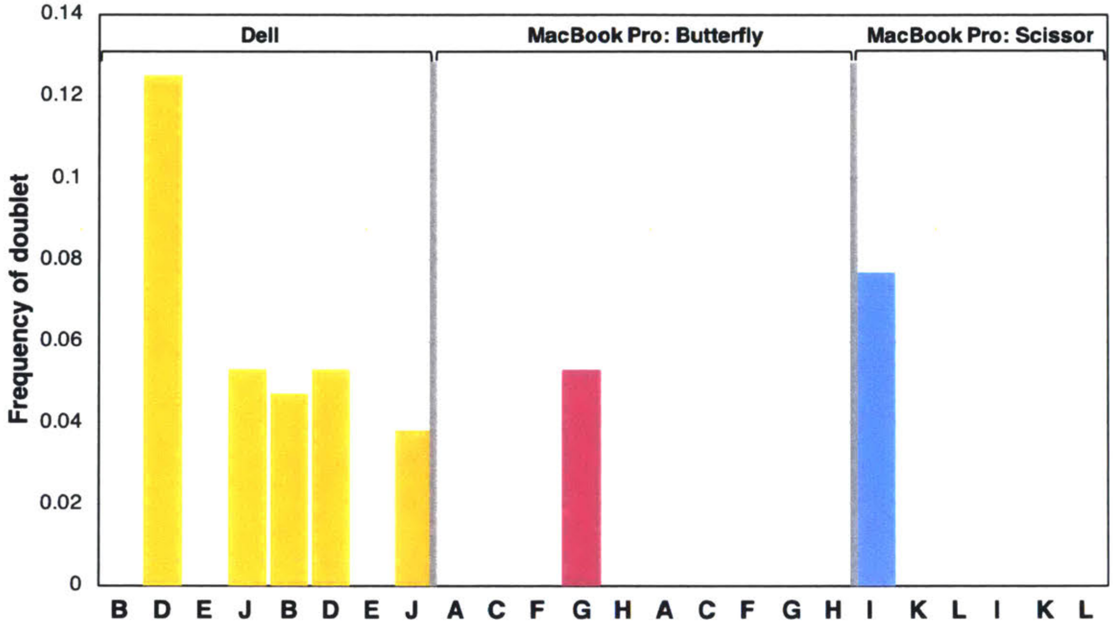

Figure 4.16: Frequency of doublet by mistake type and individual participant. Comfortable speeds are listed first.

Surprisingly, the butterfly mechanism keyboard type, which has caused much customer dissatisfaction due to its tendency for keys to stick and type doublets (described in Section 2.4.3), is the keyboard type with the lowest cumulative frequency of doublets typed. Of the 5 participants with two averages each, only one average was nonzero, indicating that a nonzero amount of doublets occurred on the mechanism only one time out of ten (10%). These data do not demonstrate the key stickiness or tendency to type doublets as complained about by customers, and may perhaps overestimate the frequency in this own dataset as the doublet may have been intentionally typed as a misspelling (with the "hit" letter being the same as the previously hit letter) instead of resulting from a stuck key. Additionally, the doublet-typing tendency might only be present in certain defect Apple keyboards and the tested keyboards may not be defective.

4.1.7 Effects of Testing Condition on Laptop Typing Accuracy and Specific Mistake Type

Similar analysis to that done in Section 4.1.3 was completed to observe the conditions' effects on typing accuracy. Figure 4.17 displays the accuracy percentage for comfortable and fast typing. The accuracies typing without backspace were not recorded because the participant was unable to fix an error after it was made, causing a single small error to significantly impact the accuracy score far past the individual mistake.

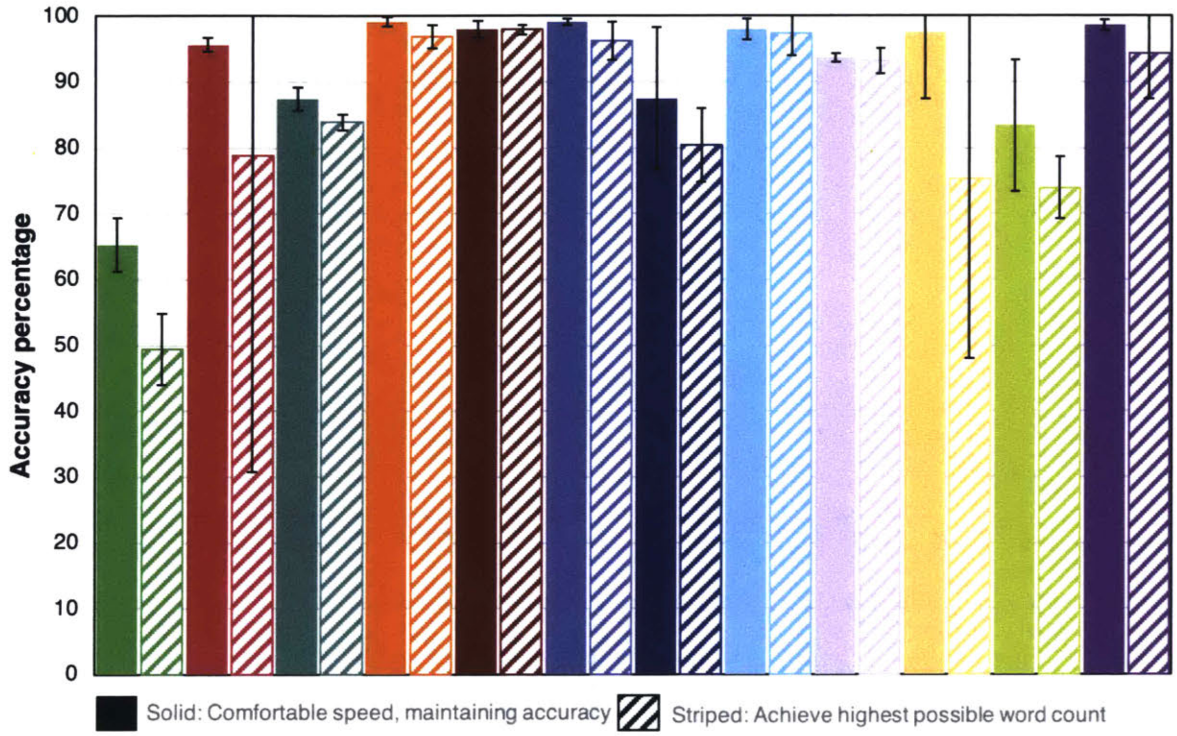

Figure 4.17: Comparing typing accuracy between comfortable typing and fast typing, colored by participant. Bars show the average typing accuracy over three trials at the specific condition.

Of all of the accuracy pairs shown in Figure 4.17, 11 of the 12 decrease in accuracy when the participant is attempting to type at a higher speed and decrease to an average accuracy of $(91.8 \pm 5.0)\%$. The one accuracy pair that did not decrease remained relatively unchanged between trials. This shows that attempting to type faster causes typists' accuracies to decrease, which is rendered statistically significant by a one-tailed t-test and a p-value of 0.0033.

The specific error types (as defined in Section 3.2.1) were analyzed to observe how the conditioned testing affected the frequencies of each mistake type. The mistake types include capitalization, bad ordering, doublet, neglect, misspelling, and punctuation. The average frequency distribution for all participants across mistake types and conditions are shown in Figure 4.18.

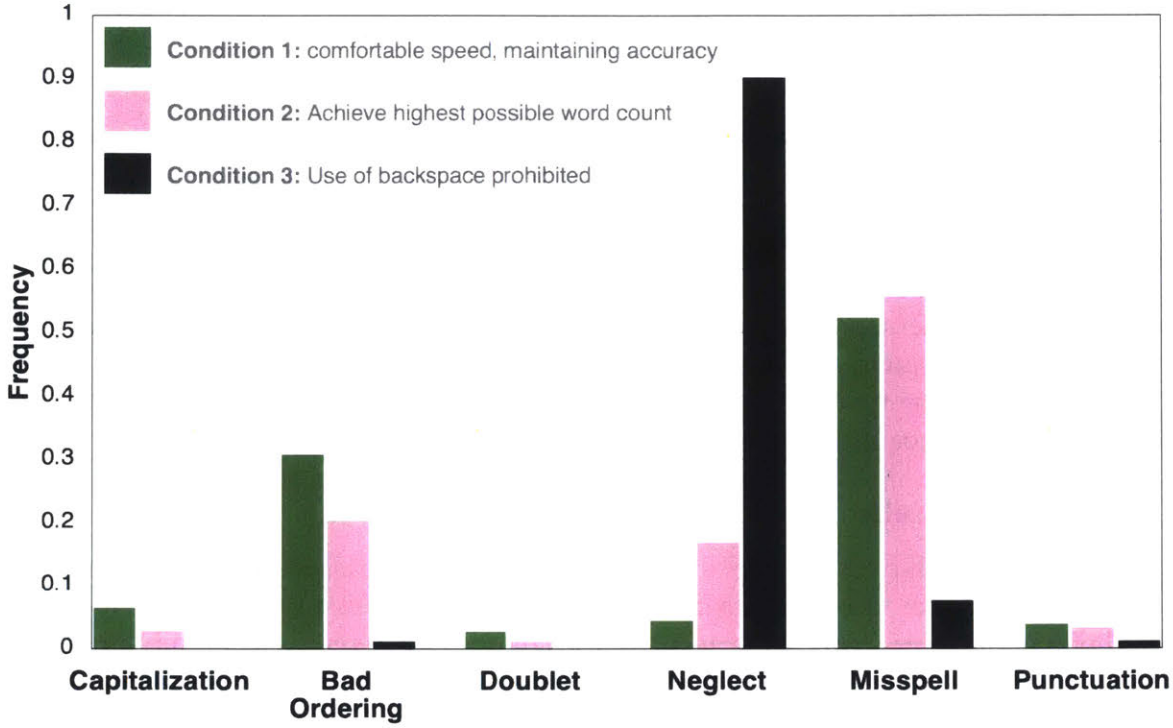

Figure 4.18: Frequency of specific mistake type by testing condition. Misspellings are the cause for most frequent typing mistakes during Conditions 1 and 2, and neglect to fix a mistake is the most frequently-occurring for Condition 3. Capitalization, doublet, and punctuation mistakes are happen significantly less frequently than misspellings and bad-ordering mistakes.

First, the Figure 4.18 as a whole is considered. Figure 4.18 clearly displays the effects of prohibiting backspace on mistakes from neglect, misspellings, and bad ordering. The frequencies from neglect appear to increase exponentially as the participant steps through the prescribed testing conditions, and the frequencies from misspellings and bad orderings dramatically decrease between the first two conditions and the last condition.

Next, specific conditions are considered. The first set of comparisons considered the differences in mistake frequency between comfortable typing and typing as fast as possible. Attempting to increase typing speed proved to have two statistically significant effects out of the six mistake types. The first statistically significant effect was in the increase in neglect error frequency from an average of 0.043 during comfortable typing to 0.169 for fast typing, which is about 4 times more common than the original frequency. This conclusion is rendered statistically significant by a one-tailed t-test and a resulting p-value of 0.006. The second statistically significant effect was in the decrease of capitalization error frequency to about half its original frequency value.

The second set of comparisons considered the differences in mistake frequency between comfortable typing and typing without "Backspace". Restricting participants from typing with mistake-erasing assistance produced five statistically significant effects out of the six mistake types. Capitalization, bad ordering, doublets, and misspelling mistakes all decreased in frequency. Capitalization and doublet errors decreased in frequency to 0% from 6.5% and 31% respectively. Bad ordering frequency decreased by a factor of 28 and misspelling frequency decreased by a factory of 7. They were all rendered statistically significant by one-tailed t-tests and resulting p-values of 0.0065 (capitalization), 2.65×10^{-5} (bad ordering), 0.029 (doublet), and 3.98×10^{-5} (misspelling). Frequency of mistakes from neglect to fix mistypes increased significantly by a factor of 20 and is proven statistically significant with a p-value of 3.26×10^{-6}.

The conclusion that attempting to type at a faster speed will increase neglect errors are supported by the verbal comments of the participants, who stated that they didn't have time to go back and fix mistakes. These comments reflect that participants were focusing on speed, as directed, and therefore prioritized completing the passage quickly over maintaining accuracy. The conclusion that disallowing the use of "Delete" or "Backspace" keys decreased the frequency of capitalization, bad ordering, and misspelling mistakes shows that typists were being more deliberate with their typing, therefore making them less likely to make any type of error. As expected, the only error type that increased under these conditions was errors from neglect, because the typist was not allowed to fix a mistake.

4.2 Phone Trial Results

Phone trials were conducted through the transcription of four passages on both familiar and unfamiliar keyboards (as described in Section 3.2.4) and completion of 3 typing tests on the mobile phone application TapTyping to obtain a comfortable typing speed and specific error types. The results from passage transcriptions concluded that typing on an unfamiliar phone consistently decreases that participant's typing speeds to approximately 50% of their original speed. Similarly, disabling Autocorrect for participants who regularly use Autocorrect causes typing speeds to decrease to approximately 80% of their original speed. Participant sex and undergraduate major do not affect typing speed. The most frequent mistakes performed when typing on phones are misspellings and incorrectly-timed spaces which together account for about 90% of the total mistakes. A closer analysis of the miss-hit directions on phones shows that individuals tend to underreach more often than overreach for keys and both hands more frequently hit letters toward the middle of the keyboard. The following sections display the raw data and analyzed results that are summarized here.

4.2.1 General Results on Phone Keyboard Familiarity

Similarly to the comparison discussed in Section 4.1.1, the phone passage transcription times between personal and unfamiliar phone keyboards were compared to observe the effects of device familiarity on typing speed. This analysis utilized the results from the tests described in Section 3.2.4, where the participants were asked to perfectly transcribe four passages on both their personal mobile phone and an unfamiliar Droid Razr M phone, both with Autocorrection enabled. A third transcription was added to each passage to measure the time taken to transcribe the passage with Autocorrect disabled on the personal phone. This third transcription is discussed in Section 4.2.2. All participants used two thumbs to type on their mobile phone, and typed in the "hunt and peck" style mentioned in Section 2.2.

The transcription times were compared between familiar and unfamiliar phone keyboards for each participant to observe how their typing speed changed as a function of familiarity. Figure 4.19 correlates participants' familiar phone typing speeds to their unfamiliar phone typing speeds.

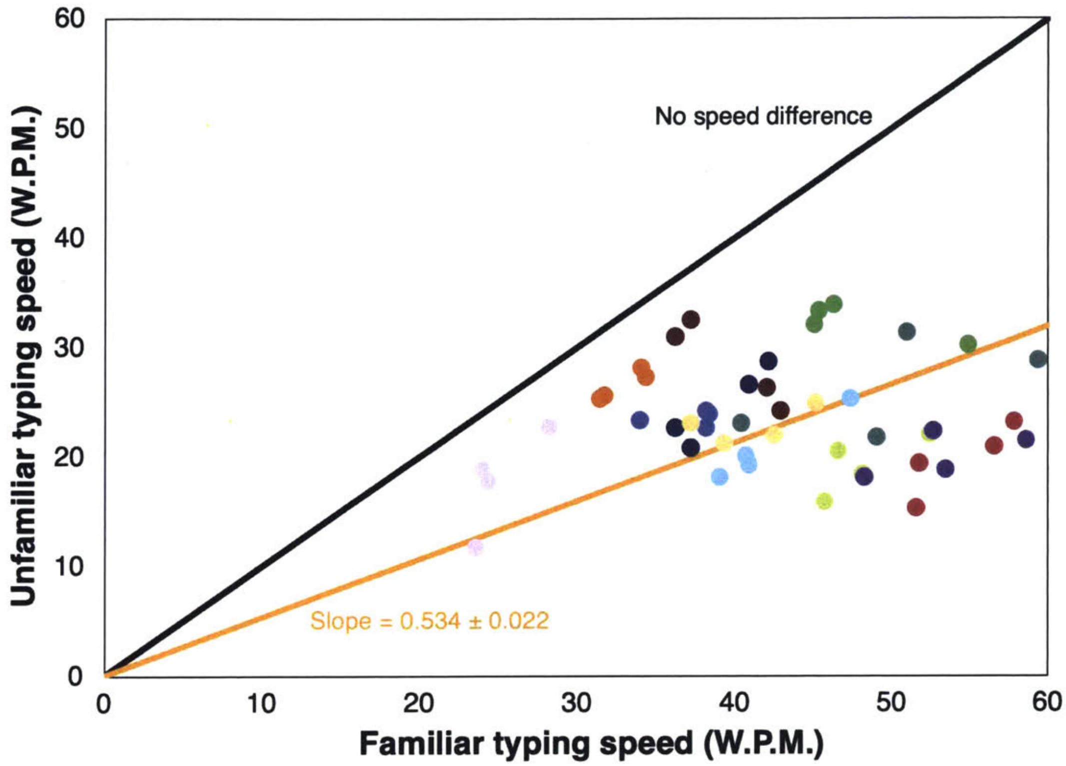

Figure 4.19: Correlation of familiar phone typing speed to unfamiliar phone typing speed, colored by participant. Diagonal line y = x represents no difference in typing speed. All dots lie below the line, indicating that all participants' typing speeds were slower on the unfamiliar keyboard. The orange line shows the data's trend, following y = (0.534 ± 0.022)x.

For each of the 48 trials, the typing speed on the unfamiliar phone was slower than their typing speed on the familiar phone for the same passage. This is seen by the fact that all data points fell below the y = x line that indicates no change in speed between the two conditions. The data was proportionally fit to y = (0.534 ± 0.022)x and shown as the orange line in Figure 4.19. A slope of 1 is not within the uncertainty range of the slope of the proportional fit, and therefore there is a statistically significant difference in the two slopes. However, the spread of the data causes the fit to not fully characterize the trend or location of data points throughout the trials.

Percent increases in typing speeds were calculated to observe trends in the typing speeds across participants. The percent increases in typing speed are shown in Figure 4.20.

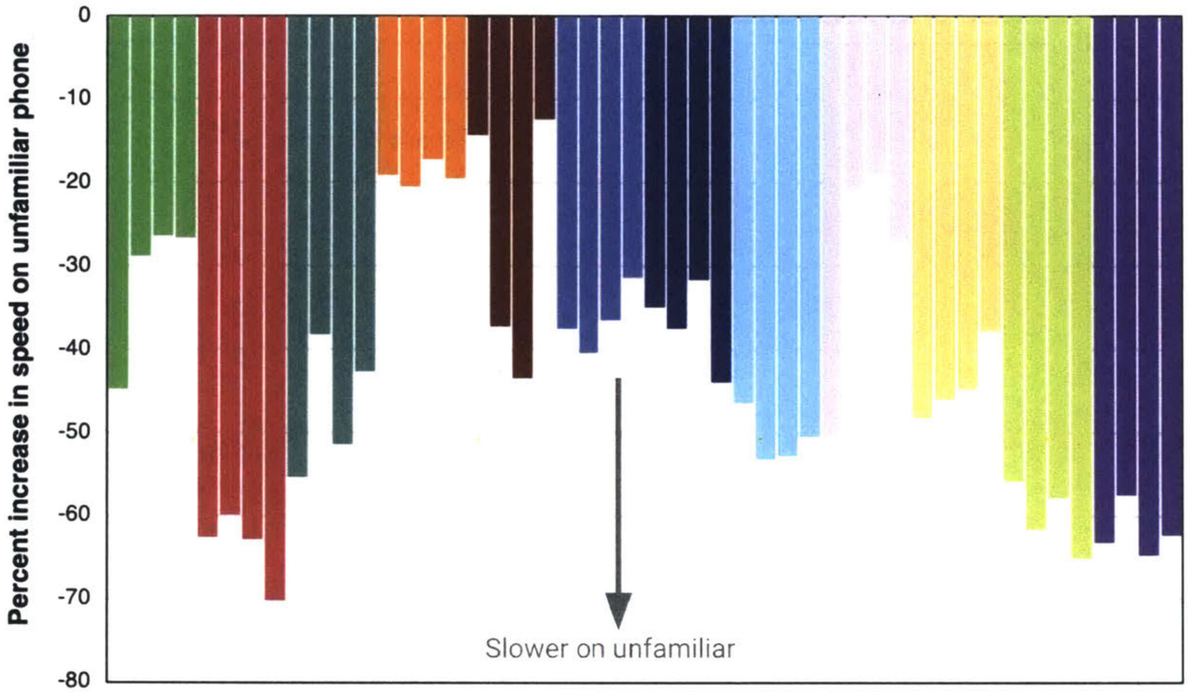

Figure 4.20: Percent change in phone typing speeds between typing on familiar and unfamiliar phone keyboards, colored by participant. The four bars for each participant display the four passage results. Bars below the zero line indicate a negative percent change, or decrease in typing speed, where the participant typed slower on the unfamiliar keyboard than on the familiar keyboard.

Every pair of tests resulted in a negative percent change in typing speed, indicating that the typing speeds were slower for every pair of tests. The percent decrease in typing speed on the unfamiliar phone ranged from 12% to 70%. Beyond the fact that all percent increases were negative when typing on the unfamiliar phone, there is no consistent trend in the magnitude of percent change across all trials and participants.

Participants' typing speeds decreased to an average of $(46.5 \pm 4.4)\%$ the original speed on the unfamiliar phone. A one-tailed t-test confirms the statistical significance of this conclusion with a p-value of 0.9×10^{-5}, lower than the statistically significant boundary of 0.05. The hypothesized mean difference between typing speeds is 16.5 words per minute.

The conclusion that phone unfamiliarity decreases typing speed to an average of 46.5% of the typist's original speed makes sense because of the difference in keyboard size between the two phones. In this experiment, typists had little experience with the new keyboard and therefore did not have the chance to increase their skills with the new phone. However, this result may have been amplified by the previously proven decrease in typing speed due to decreased keyboard size (discussed in Section 3.2.2). To determine the pure the effects of familiarity and mitigate the effects of keyboard size, devices of similar size should be chosen in the future. Should future trials be conducted, typing speed should also be tracked as the participant gains more experience with the unfamiliar phone model in hopes of characterizing the learning curve that governs typing on a new device.

To observe the trends in percent change, the percent increase for all four trials across all twelve participants were organized into a histogram and shown in Figure 4.21.

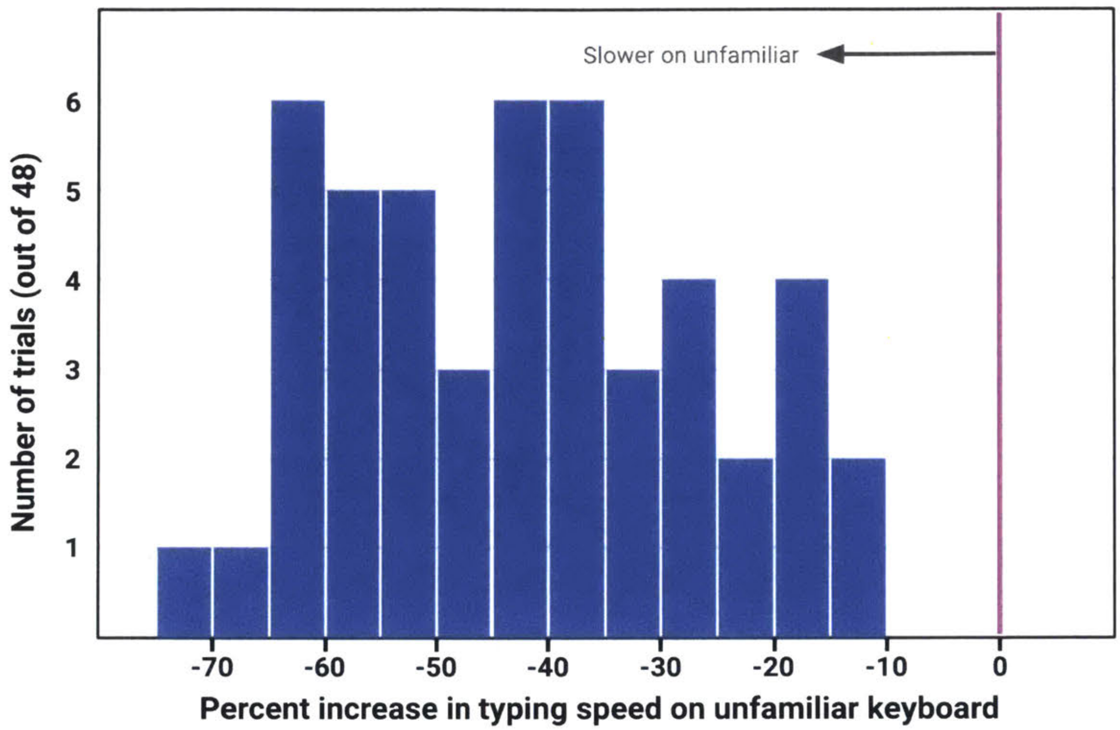

Figure 4.21: Histogram of the percent differences in typing speeds on phone keyboards. Magenta line at x = 0 indicates that there was no difference in typing speed between familiar and unfamiliar phone keyboards. All bars lie left of the zero line, indicating that all typing speeds on the unfamiliar keyboard were slower than the related typing speeds on the familiar keyboard.

As reiterated in Figure 4.21, the percent increases for all trials and participants lie to the left of the x = 0 (no change in speed) line. The data appear to be normally distributed and are approximately centered at -40% increase.

4.2.2 Effects of Autocorrection on Phone Typing Speed and Accuracy

The effects of Autocorrection on speed and accuracy when typing on a mobile phone were investigated through the repeated transcription of four passages with and without Autocorrection enabled. Figure 4.22 correlates participants' typing speed with Autocorrect enabled to their speed with Autocorrect disabled.

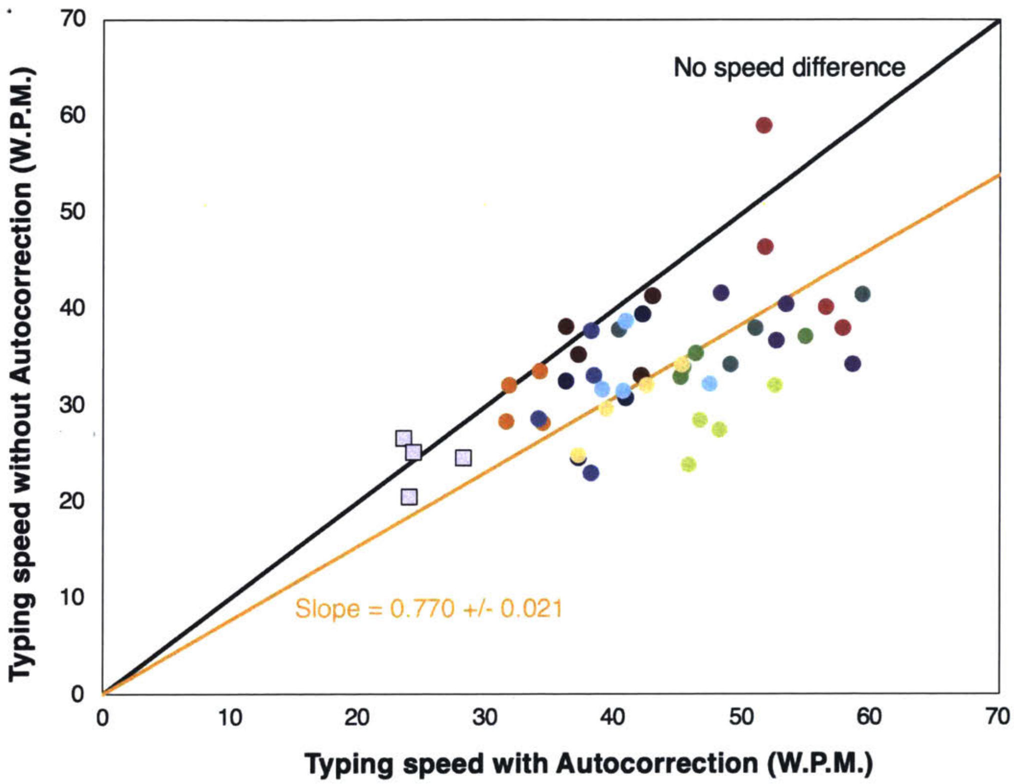

Figure 4.22: Correlation of typing speed with Autocorrection enabled to typing speed with Autocorrection disabled, colored by participant. Diagonal line y = x represents no difference in typing speed. Dots below the line indicate that the participant's typing speed was faster with Autocorrection enabled, and those above the line indicate that the speed was faster with Autocorrection disabled. Light purple squares outlined in black indicate the participant who regularly disables Autocorrect. The orange line shows the data's trend (not including the participant who regularly disables Autocorrect), following $y = (0.770 \pm 0.021)x$.

As seen in Figure 4.22, the data mostly fall below the $y = x$ line indicating that individuals more frequently type slower with than without Autocorrection. Of the trials with individuals who regularly use Autocorrect, only 3 out of 44 trials were typed faster without Autocorrect. The participant who regularly disables Autocorrect was not included when calculating the data's proportional fit. The data follows the line $y = (0.770 \pm 0.021)x$.

To analyze trends in the percent increases when typing without Autocorrect, the percent increases in typing speed were then calculated and shown in Figure 4.23.

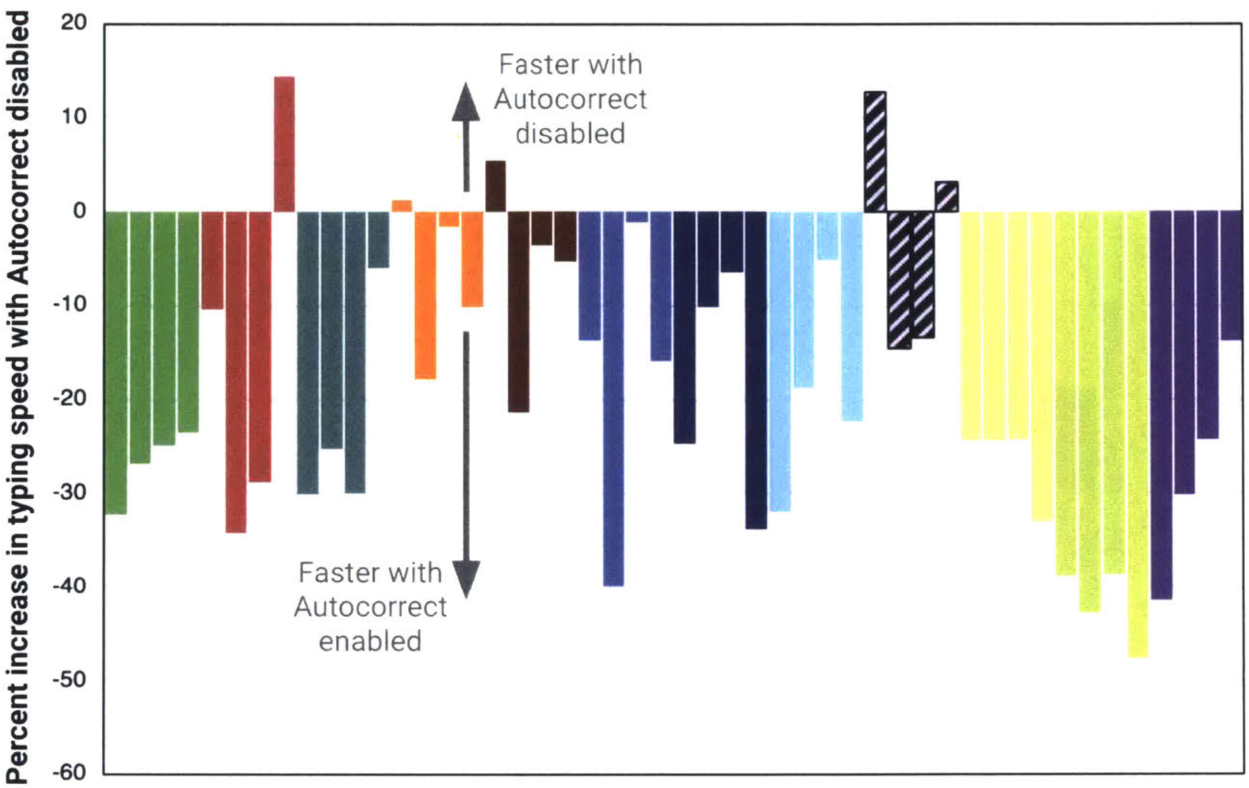

Figure 4.23: Percent change in typing speeds between typing with Autocorrect enabled and disabled, colored by participant. Bars below the zero line indicate a negative percent change, or decrease in typing speed when typing with Autocorrect disabled. The participant who regularly disables Autocorrect is denoted by purple and black striped bars.

Figure 4.23 reiterates that a majority of typing speeds decrease when Autocorrect is disabled, as only three trials saw increases in speeds (for participants who regularly enable Autocorrect). The individual who regularly disables Autocorrect both increased (for two trials) and decreased (for two trials) in typing speeds across his four trials, with the percent increases averaging out to approximately 0 indicating that there is no consistent trend in his percent increases.

Removing Autocorrect decreases individuals' mobile phone typing times by an average of 20.9 ± 4.2% of the speed with Autocorrection enabled (not including the participant who normally disables Autocorrection for typing). The difference in trial times is deemed statistically significant by a one-tailed t-test, with a p-value of 3.48×10^{-11}. The concluded increase in typing speed validates typists' dependency on Autocorrection by demonstrating benefit of efficiency which is gained through utilizing Autocorrect.

4.2.3 Effects of Sex on Phone Typing Speed

The typing speeds found by transcribing four passages were examined between participant sexes. The speeds for each passage by each participant, colored by sex, is shown in Figure 4.24.

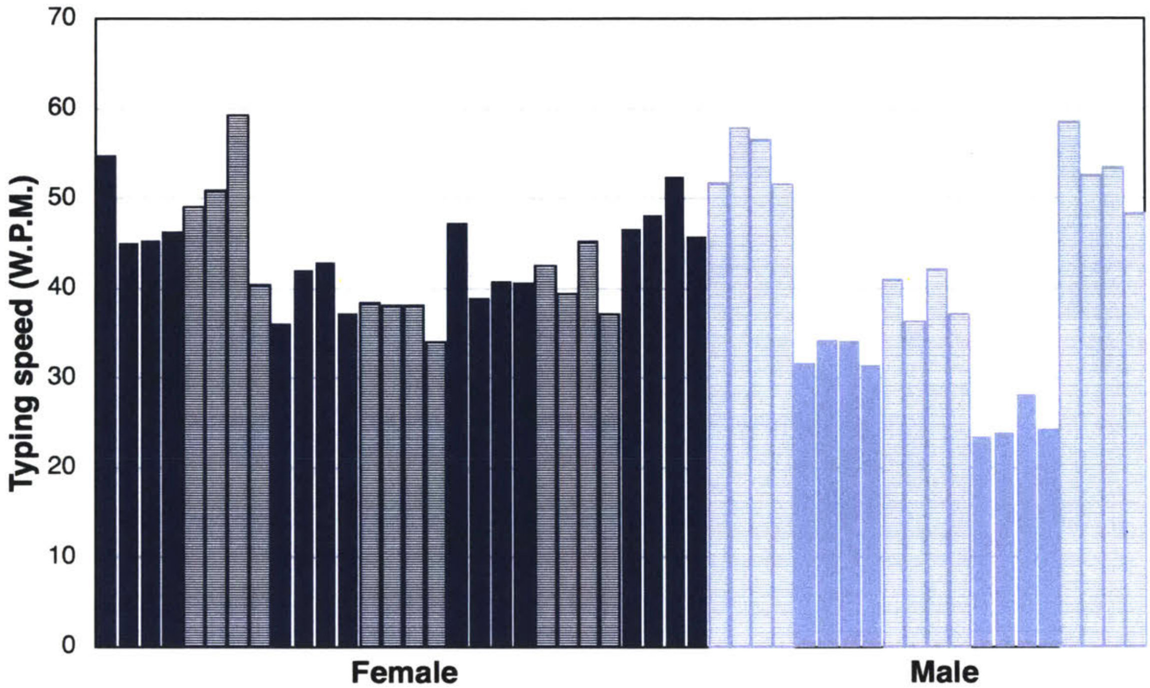

Figure 4.24: Four instances of comfortable phone typing speed per participant, organized and colored by sex. Individual participants are distinguished with alternating filled and striped bars.

Similar trends are seen in Figure 4.24 as were seen in Figure 4.11, where there is a large range of speeds for the male participants but no apparent general trend for the sexes overall. The average phone typing speed was found to be 43.7 ± 2.2 words per minute for females and 41 ± 5.3 words per minute for males. However, there is no statistically significant difference between the complete sets of data for each sex ($p = 0.355$). Extending the findings of Dennis J. LaBonty (LaBonty, 1981) that found no relationship between finger thickness or sex and computer typing speed, it follows that phone keyboards would follow the same trend and not be governed by a relationship between sex and phone typing speed.

4.2.4 Effects of Undergraduate Major on Phone Typing Speed

The typing speeds found by transcribing four passages were then examined on the basis of participant undergraduate major. The speeds for each passage by each participant, colored by undergraduate major, is shown in Figure 4.25.

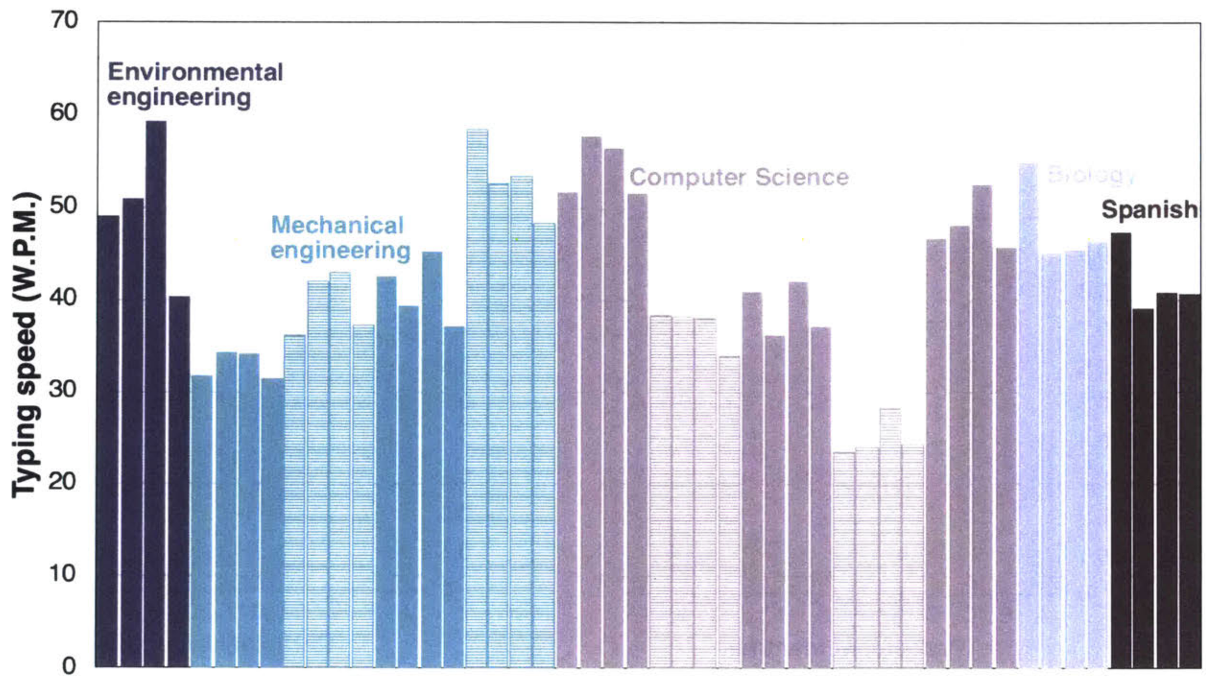

Figure 4.25: Four instances of comfortable phone typing speed per participant, organized and colored by undergraduate major. Individual participants are distinguished with alternating filled and striped bars within majors with more than one individual represented.

Similarly to Figure 4.12, Figure 4.25 does not show an immediate trend in typing speed for each major. The average typing speeds were all found to be between 40 and 50 words per minute, and no majors groupings produced a statistically significant p-value during a one-tailed t-test, indicating that none of the data set groupings are statistically significant.

The average phone typing speed was found to be 49.9 ± 7.6 words per minute for environmental engineering majors, 41.7 ± 4.0 words per minute for mechanical engineering majors, 40.8 ± 6.6 words per minute for computer science majors, 47.9 ± 4.6 words per minute for biology majors, and 42.0 ± 3.6 words per minute for Spanish majors. Despite small variation in the average speeds for each major, none of the data sets are statistically significant. For future tests it is recommended to gather a larger and more diverse group of individuals so that there are at least 10 individuals representing each major and that the chosen individuals are of random age, gender, and other characteristics.

4.2.5 *Frequency of Mistake Type on Phone Keyboards*

Similarly to the comparison done in Section, 4.1.6., mistakes performed by each participant in each trial were recorded to be compared in frequency. The categories of mistakes on phone keyboards are incorrect spaces, misspellings, punctuation, and other. Mistakes categorized as "Other" include participants instinctively selecting the correctly-spelled word as recommended by Autocorrect. Each participant's number of a specific error type was divided by the total number of errors performed by that individual in order to normalize the data and provide only the frequency of that error type. The frequencies of specific error types by participant when typing on their personal phone is shown in Figure 4.26: a) through d).

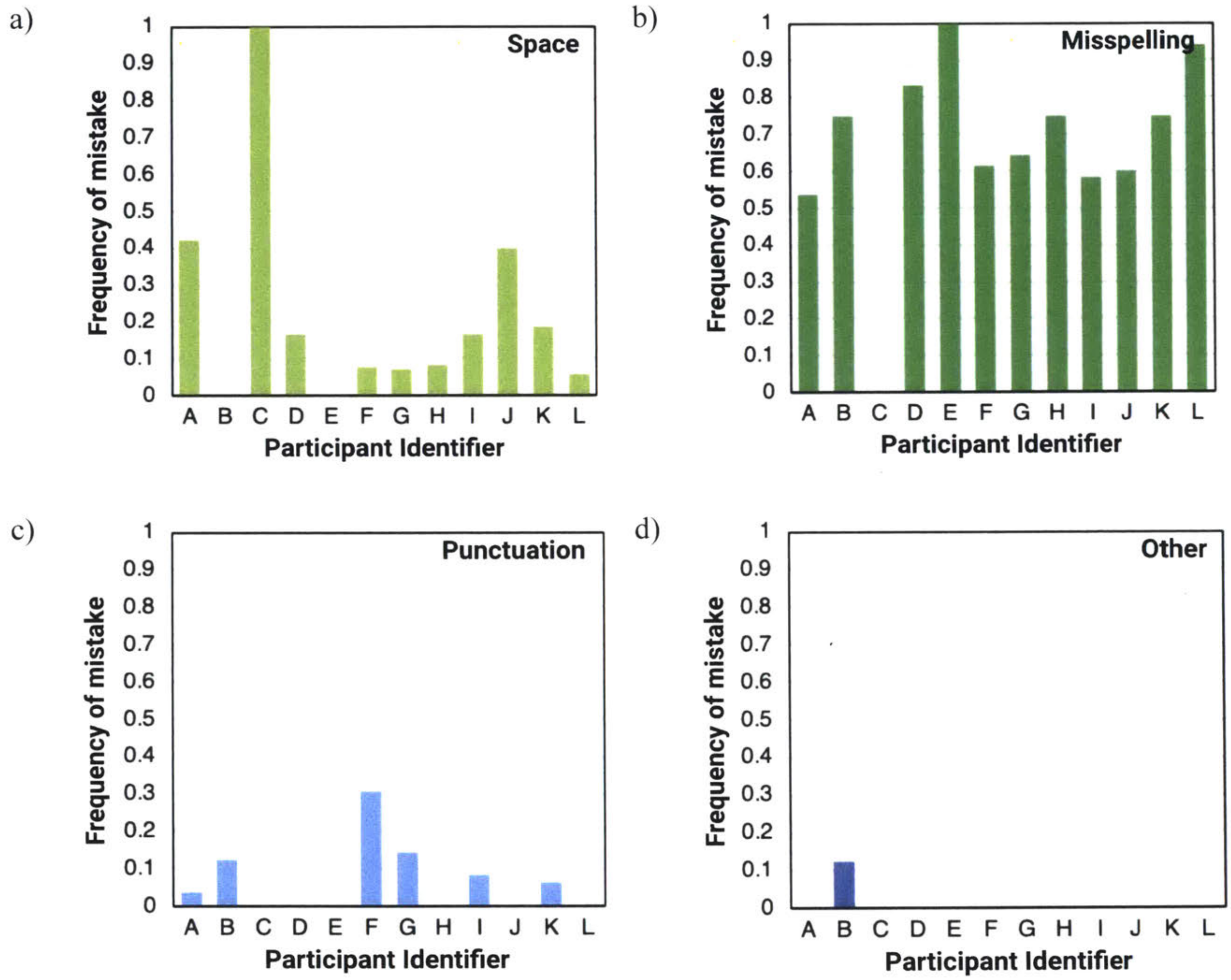

Figure 4.26: (a) Space, (b) misspelling, (c) punctuation, and (d) other mistake types. Here, the one instance of "other" happened when the participant instinctively tapped on the word recommended by Autocorrect without completing the word themself.

Upon first glance at Figure 4.26, it is apparent that misspellings are the most frequent mistake type when typing on mobile phones. The second most frequent mistake is incorrectly located spaces. The data shown in Figure 4.26: a) through d) was compiled to produce an average frequency for each mistake type. The average frequencies by mistake type are shown in Figure 4.27.

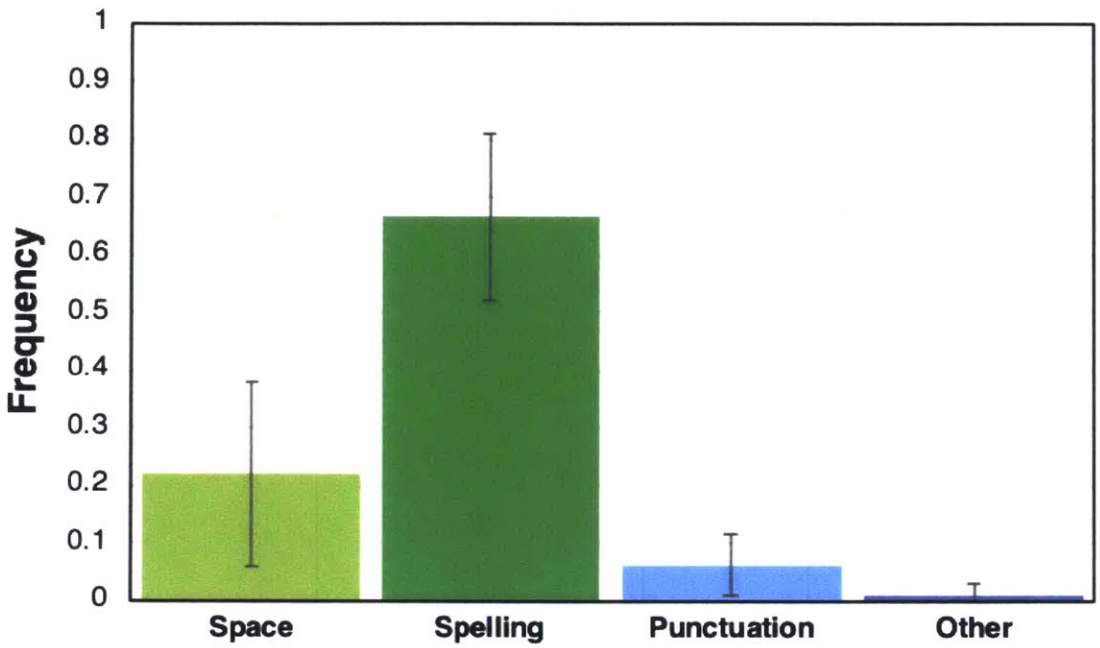

Figure 4.27: Average frequency by phone typing mistake

Figure 4.27 indicates that misspellings and incorrectly-timed spaces together account for nearly 90% of mobile phone typing mistakes. Following a similar logic process as discussed for mistake frequency when typing on laptops, it appears to be logical for punctuation errors to be much less frequent than spelling errors. Punctuation characters are more sparse than letters and spaces in a majority of English sentences, therefore providing less opportunities to make a punctuation typing error. Even though the typing style for texting on a mobile phone often neglects to include punctuation, the sparsity of punctuation in the requested passages overcame the foreignness of using punctuation and led to a logically low frequency of punctuation errors.

4.2.6 Critical Evaluation of Misspellings on Phone Keyboards

The data gathered from the TapTyping test provided the opportunity to conduct a deeper evaluation of the misspellings that occurred during the typing tests. By rewatching the 'Instant Replay' for each of the participants' three trials, it was possible to gather a list of 'Intended' keys and their corresponding 'Hit' keys (as described in the latter part of Section 3.2.3). There were 58 distinct misspelling pairings, and the complete list with their occurrence frequencies is found in Appendix D. The most frequent misspelling letter pairs are seen in Table 4.2.

Table 4.2: Most frequent misspelling letter pairs when typing on mobile phone

Intended	Hit	Frequency
d	s	5
i	u	5
s	d	5
i	o	4
r	e	4
a	s	3
c	x	3
e	r	3
h	b	3
h	j	3
o	k	3
u	j	3

Analysis was conducted into the misspelling set to characterize that direction the mistakes occurred most frequently. After gathering a complete list of all misspellings during the mobile phone typing tests, miss-hit directions were added. For example, intending to type a 'd' and actually typing 's' was labeled as an 'Immediate left' hit, as 's' is located immediately left of the letter 'd'. Similarly, intending to hit a 'g' and actually typing 'v' was labeled as 'Left down diagonal' because the typed letter is located diagonally down and to the left of the original letter 'g'. The letters that were more than two keys away from the intended letter were regarded as 'Incorrect hit', such as hitting 'a' when the intended letter is an 'o'. The frequency of hit locations, regarding the origin as the location of the intended key, is shown in Figure 4.28.

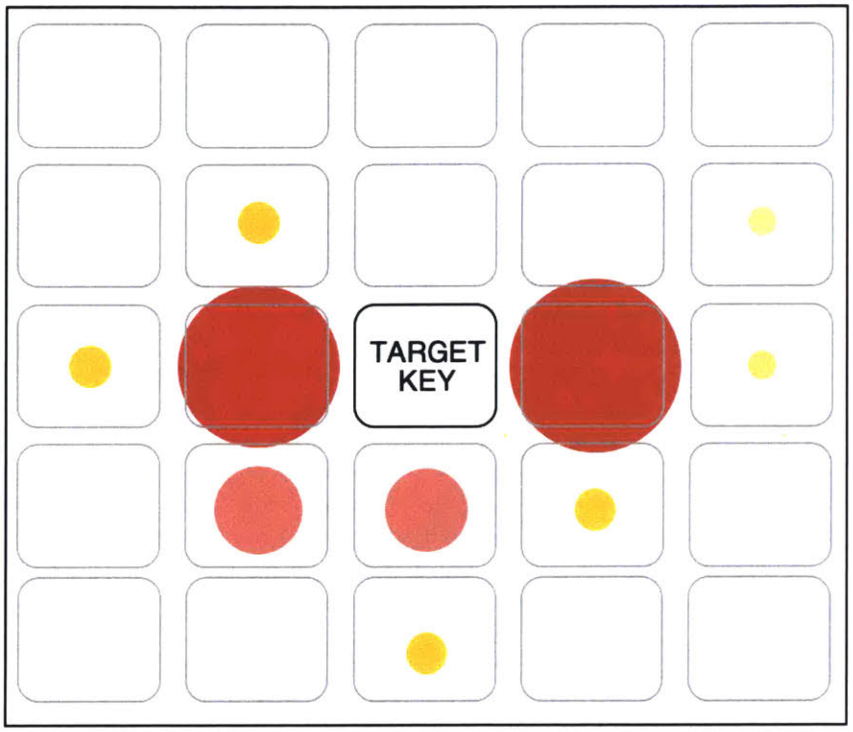

Figure 4.28: Frequency of miss-hit directions in relation to the intended key. Larger sized dots indicate a higher frequency of mistake at the dot's center. Grid behind demonstrates key spacing on phone keyboards. Key offsets from the target key vary based on the location of the intended key and may not be organized into a grid as demonstrated here.

Figure 4.28 shows that the most frequently miss-hit directions are in the same row as the intended key, only missing to the right or left of the intended key. These data suggest that individuals are more likely to miss to the right of the intended key (32.4%) than to the left (28.6%). Typists were more likely to mistype the letter that is below than above the target letter. Mistakes involving overreaching (typing above the intended key) as indicated by dots above the "Target Key" row in Fig 4.28 were responsible for 2.9% of all errors. Mistakes involving underreaching (typing below the intended key, indicated by dots below the horizontal line) were responsible for 20.0% of all errors, which was one third of the right/left errors and almost 7 times greater than the overreaching errors.

The conclusion that underreaching is significantly more frequent than overreaching goes against the hand's natural resting position, which includes a straight and relaxed thumb (Adams, 2017). Therefore to reach the bottom row keys or space bar the thumb had to be significantly bent, going against the thumb's natural resting position. However, the higher frequency of underreaching is supported by the body's tendency to minimize extraneous movement. For example, it requires more effort to reach for a letter on the upper row of a keyboard than to hit a letter closer to the phone's bottom. Therefore, these results demonstrate that body's tendency to minimize extraneous movement overpowers the hand's natural resting position, resulting in more frequent underreaching than overreaching.

Miss-hit directions were separated by their responsible hand and then further analyzed to determine if the miss-hit direction was dependant on the hand that was typing the letter. A diagram showing the letters and letter location for each responsible hand are shown in Figure 4.29. The left hand is responsible for typing fourteen letters, the right hand is responsible for typing eleven letters, and "B" is unassigned because it is equidistant from the home keys for both hands' index fingers (the 'f' and 'j' keys).

Figure 4.29: Keyboard layout with letters coded by responsible hand. Letters on the left side of the keyboard, therefore falling under the responsibility of the left hand, are shown in dark grey. Letters on the right side of the keyboard, therefore falling under the responsibility of the right hand, are shown in light grey. "B" is shown in white as it is unassigned to a hand.

Miss-hit directions, once separated by their responsible hand, concluded that the left and right hands both tended to miss-hit letters toward the middle of the keyboard. For example, letters on the left side of the keyboard (typed by the left hand) more frequently miss-hit to the right of the intended key, which is closer to the keyboard's middle line than was the intended letter. Letters that were typed by the left hand mistyped to the right of the intended letter with 51.1% frequency. Letters that were typed by the right hand mistyped to the left of the intended letter with 58.3% frequency.

The conclusion that typists more often miss-hit toward the middle of the keyboard follows the aforementioned natural resting position of thumbs. When typing on a mobile phone, the thumbs are in a straighter orientation while aimed at the middle of the keyboard. Therefore the hands' tendency to type towards their natural resting position is physiologically supported.

4.3 Laptop vs. Phone Comparison Results

Laptop and phone trials were compared across the tests that were described in Sections 4.1 and 4.2. It was found that participants had surprisingly similar typing speeds when typing on their phones and laptops, with 30% of trials having a faster typing speed on their phones than on their laptops.When the results from all participants were grouped together, the typing speed on phones were statistically significantly slower than on laptops, with a speed ratio of (80.2 ± 4.2)%.

4.3.1 Comparing Typing Speeds on Laptop and Phone Keyboards

To compare typing speeds between the two device types, speeds were recorded for each participant from their "Condition 1: Comfortable speed, maintaining accuracy" trials described in Section 3.2.1 and TapTyping phone typing tests described in Section 3.2.3. Figure 4.30 correlates participants laptop typing speed to their phone typing speed.

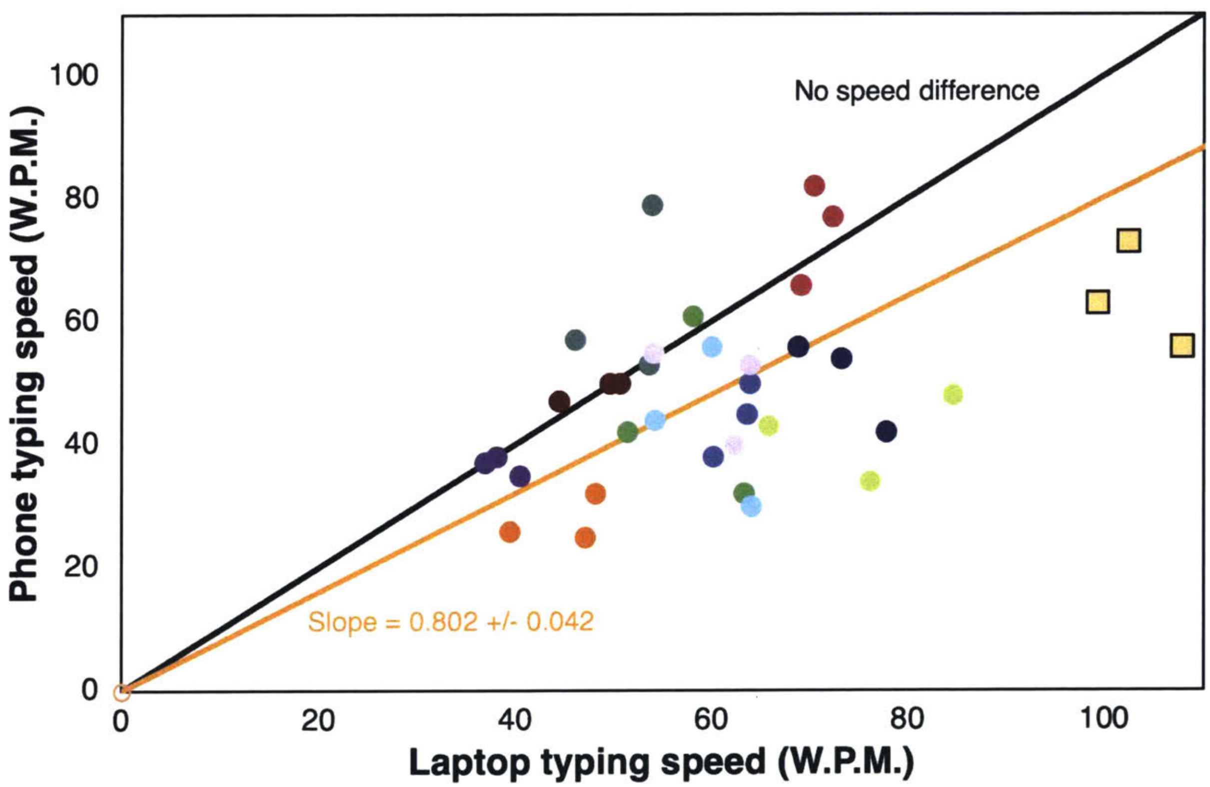

Figure 4.30: Correlation of laptop typing speed to phone typing speed, colored by participant. Diagonal line y = x represents no difference in typing speed between devices. The orange line shows the data's trend (not including the participant who types significantly above the average typing rate, denoted with outlined orange squares), following y = (0.802 ± 0.042)x.

Figure 4.30 shows no immediate apparent relationship between laptop typing speed and phone typing speed, other than the slight tendency for individuals to type slower on phones than on laptops. The data was characterized by a proportional fit that follows y= (0.802 ± 0.042)x, indicating that individuals who type at faster speeds on their laptops see more drastic changes in speed when typing on their phone. The participant who types significantly above the average typing rate was excluded during the creation of the proportional fit. The fit is surprisingly close to the equal speed line y = x, shown in black.

The participants' typing speeds decreased to an average of (81.94 ± 7.81)% of the laptop typing speed when typing on a mobile phone. The speed changes between trials for all twelve participants ranged from a decrease of 25.11 words per minute to an increase of 51.86 words per minute ((44.7% to 146.6)% of participant's laptop typing speed) when typing on a mobile phone. Surprisingly, not all participants experienced decreases in typing speed. 10 of the 36 trials (27.8%) typed at a higher speed when typing on a phone versus on a laptop keyboard.

To better understand the general trend for each individual, each participant's average percent change in typing speed are shown in Figure 4.31.

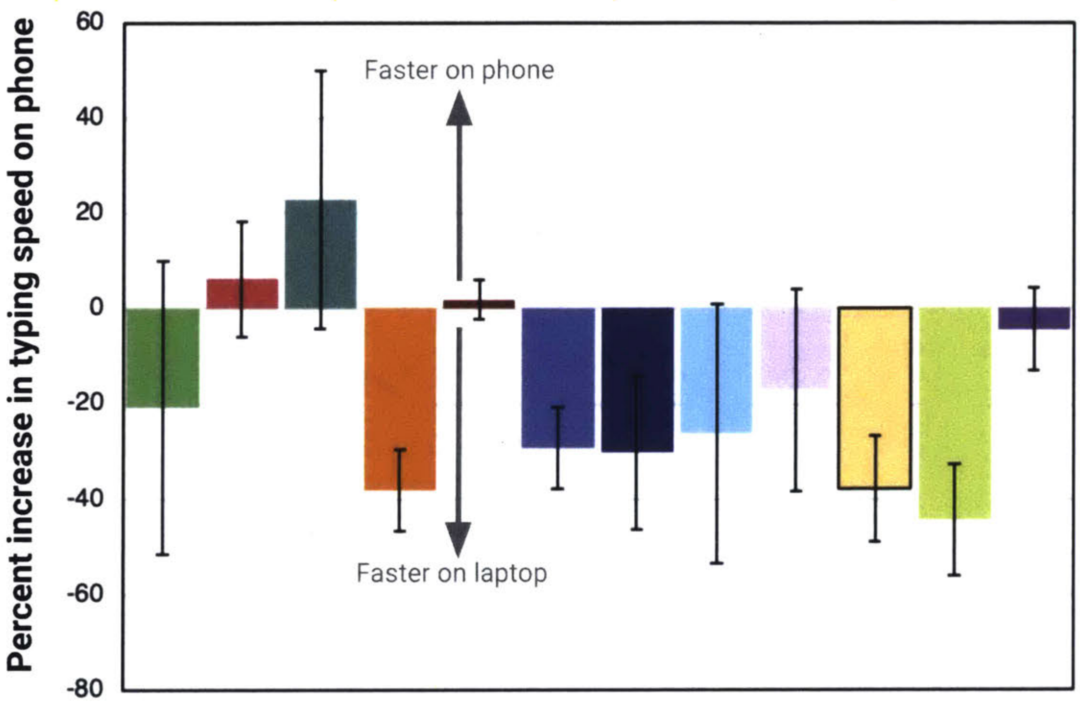

Figure 4.31: Percent change in typing speeds between between typing on laptops and phones, averaged and colored by participant. Participant who types significantly above the average typing rate has been denoted with an outlined bar.

As seen in Figure 4.31, a majority of participants (75%) have averages showing that they type faster on their laptops than on their phones. 7 of the 12 participants have error bars that overlap zero, indicating that these seven participants did not see statistically significant differences in speed between the two devices. The 5 remaining participants who did see statistically significant changes in speed all typed slower on their phones than on their laptops.

5. Conclusions

Both statistically significant and statistically insignificant conclusions have been drawn regarding the dependence of typing speed and accuracy on device type and familiarity. Sex and undergraduate major were not found to impact typing speed on laptops or phones.

Analysis of the laptop typing trials concluded that participants tend to either decrease or remain unchanged in typing speed when typing on an unfamiliar laptop. Laptop device familiarity was determined through physical attributes such as dimensions and materials, as discussed in Section 2.4: Laptop Keyboard Specifics. The level of familiarity was proven to impact laptop typing speeds, showing that users of each of the three keyboard models were more likely to slow or remain consistent in typing speed than increase in typing speed on an unfamiliar laptop. Users who regularly typed on keyboards that were more similar to the unfamiliar AmazonBasics keyboard were most likely to remain consistent in typing speed. Users who regularly typed on dissimilar keyboards to the unfamiliar AmazonBasics keyboard were most likely to decrease in typing speed.

Analysis of the phone typing trials concluded that participants consistently decrease in speed when typing on an unfamiliar phone. This average decrease was to approximately 50% of the original speed.

The specific mistake types for phone and laptop typing were recorded to observe their distributions. Misspellings and bad ordering, a subset of misspellings where the misspelling involves the correct letters simply typed in the wrong order, are found to be the most frequent error types when typing on laptops. Misspellings (discluding bad ordering) account for approximately 50% of typing errors on personal laptops and bad ordering accounts for approximately 30% of typing errors on personal laptops. The remaining mistake types (capitalization, doublets, neglected mistake, and punctuation) account for less than 10% of typing errors on personal laptops. Although Apple customers have been recently frustrated with the butterfly mechanism's tendency to have sticky keys that type doublets, it was here found to be the least frequent keyboard model generator of doublet mistakes.

Misspellings and incorrectly-timed spaces account for 2/3 and approximately 1/5 of mobile phone typing mistakes respectively. Analyzing the specific misspellings that were performed concluded that individuals are more likely to miss to the right of the intended key (32.4%) than to the left (28.6%) and are more likely to mistype a the letter that is below (underreaching, 20.0%) than above (overreaching, 2.86%) the intended letter. Both the left and right hands are more likely to miss-hit letters toward the middle of the keyboard. Letters that were typed by the left hand mistyped to the right of the intended letter with 51.1% frequency. Letters that were typed by the right hand mistyped to the left of the intended letter with 58.3% frequency.

The absence of Autocorrection decreases individuals' mobile phone typing times by an average of approximately 20% of the speed with Autocorrection enabled.

Requesting that the participant type to achieve the highest possible word count did not affect the participants' typing speed when compared to their comfortable speed. However, when prohibited from utilizing the "Backspace" or "Delete" key, the participants typed at speeds that were approximately 90% of their comfortable typing speeds, indicating that typing speed decreases when mistake-erasing is prohibited. When attempting to achieve the highest possible word count, the frequency of errors from neglect increased to 4 times the original frequency value. When prohibited from utilizing the "Backspace" or "Delete" key, capitalization, bad ordering, and misspelling mistakes decreased in frequency. Frequency of mistakes from neglect to fix mistypes increased significantly by a factor of 20.

Participants are more likely to type slower on their phone than on their laptop, typing at an average of $(82 \pm 8)\%$ of their laptop speed when on their phone. However, 10 of the 36 trials (approximately 28%) typed faster on their phones than on their laptops. This is a surprising result as laptop keyboards are larger, include tactile feedback that was found to increase typing speeds (Brewster, 2007), and use more fingers when typing. This result may be the result of increasing phone popularity throughout the years, where individuals use their phones more frequently to replace tasks that were previously completed on computers such as messaging, sending emails, and posting on social media. By using their phones more frequently, typists are further familiarizing themselves with their phone's soft keyboard and therefore likely increasing their phone typing speeds above their laptop typing speeds.

Further testing should be pursued to characterize the learning curve of typing on new devices by comparing typing speeds during numerous passage transcriptions for a single new device. This experiment should also be completed on a larger number of devices to increase sample variety by, for example, exposing participants to a wide spectrum of keyboard styles, key mechanisms, key heights, and required key depression forces. Other future experiments should include miss-hit direction analysis for typing on a laptop keyboard in a similar analytic method as performed for mobile phones in Section 4.2.6. By acquiring the miss-hit results between this experiment and the recommended future experiments, comparisons can be drawn between typing tendencies on the two devices.

APPENDIX A.

Survey on participant demographic background and typing experience

What is your name? ____

What is your age? ____

What is your sex? _____ Male

_____ Female

_____ Prefer not to say

_____ Other

Are you a university student? _____ Yes

_____ No

If you are a university student, what is your major? ____________________________

If you are not a university student, what is your career background? ________________

Laptop trial: Background questions on personal laptop use

What type of laptop do you currently use? ____________________________

When did you start using your current laptop model? ______________________

Estimate your average weekly laptop usage: ____________________________

What kind of video games do you play? ____________________________

Estimate your average weekly video game usage: ________________________

Phone trial: Background questions on personal phone use

What type of phone do you currently use? ____________________________

When did you start using your current phone model? ______________________

Estimate your average weekly phone usage: ____________________________

APPENDIX B.

Passages for comparing by laptop keyboard familiarity

Laptop Passage 1

Mr. and Mrs. Dursley, of number four, Privet Drive, were proud to say that they were perfectly normal, thank you very much. They were the last people you'd expect to be involved in anything strange or mysterious, because they just didn't hold with such nonsense. Mr. Dursley was the director of a firm called Grunnings, which made drills.

Laptop Passage 2

Seattle is a seaport city on the West Coast of the United States. It is the seat of King County, Washington. With an estimated 730,000 residents as of 2018, Seattle is the largest city in both the state of Washington and the Pacific Northwest region of North America. Seattle is the northernmost large city in the United States.

Laptop Passage 3

Shelves are one of the most useful furnishing items in a house or office. Shelves can carry books, ornaments, tools, utensils, photos, craft projects and much more. They help you to organize, categorize, clear away and keep things neat. There are many ways to make a shelf, some easier than others, and a few of the possibilities are presented here.

Laptop Passage 4

Born circa 428 B.C.E., ancient Greek philosopher Plato was a student of Socrates and a teacher of Aristotle. His writings explored justice, beauty and equality, and also contained discussions in aesthetics, political philosophy, theology, cosmology, epistemology and the philosophy of language. Plato founded the Academy in Athens, one of the first institutions of higher learning in the Western world.

APPENDIX C.

Passages for comparing across phone familiarity and Autocorrection

Phone Passage 1

Trader Joe's is well-known to its fans for low prices on unique food items, ranging from cookie butter to turkey corn dogs. The chain is also known for its quirky culture. Employees, easy to spot in their Hawaiian shirts, go out of their way to be helpful, and plastic lobsters are used to decorate stores.

Phone Passage 2

Today, some dogs are used as pets, others are used to help humans do their work. They are a popular pet because they are usually playful, friendly, loyal and listen to humans. Dogs often have jobs, including as police dogs, army dogs, assistance dogs, fire dogs, hunting dogs, messenger dogs, herding dogs, or rescue dogs.

Phone Passage 3

All children, except one, grow up. They soon know that they will grow up, and the way Wendy knew was this. One day when she was two years old she was playing in a garden, and she plucked another flower and ran with it to her mother. Mrs. Darling cried, "Oh, why can't you remain like this forever!"

Phone Passage 4

MIT is nerd heaven, a place where that word implies nothing but muscle and credibility. We value merit, rigor, ingenuity, and real-world problem-solving. In this community, we believe as much in excellence and boldness as we do in humility and the value of failure. An open spirit of collaboration. A strong desire to make a positive impact.

APPENDIX D.

Complete list of misspelling letter pairings when typing on phone

Direction of key with respect to intended key	*Intended*	*Hit*	*Frequency*
Right up diagonal + over 1 key	a	e	1
Immediate right	a	s	3
Immediate right	b	n	1
Immediate left	c	x	3
Immediate right	d	f	2
Incorrect hit	d	n	1
Immediate left	d	s	5
Down 2 keys	e	c	1
Immediate down	e	d	1
Incorrect hit	e	m	1
Immediate right	e	r	3
Immediate left	e	w	2
Immediate left	f	d	2
Immediate right	f	g	2
Immediate left	g	f	1
Right down diagonal	g	n	1
Left down diagonal	g	v	1
Immediate down	h	b	3
Incorrect hit	h	e	1
Immediate right	h	j	3
Incorrect hit	h	o	1
Left up diagonal	h	t	1
Left down diagonal	i	j	2
Immediate down	i	k	1
Immediate right	i	o	4
Immediate left	i	u	5
Immediate right	j	k	1
Immediate left	l	k	1
Left 2 keys	m	b	1

Direction of key with respect to intended key	*Intended*	*Hit*	*Frequency*
Incorrect hit	m	e	1
Immediate left	n	b	2
Incorrect hit	n	d	1
Left up diagonal	n	h	1
Immediate right	n	m	2
Incorrect hit	o	a	2
Immediate left	o	i	2
Left down diagonal	o	k	3
Incorrect hit	o	r	2
Incorrect hit	p	r	1
Immediate right	q	w	1
Immediate left	r	e	4
Immediate right	r	t	1
Immediate left	s	a	1
Immediate right	s	d	5
Down 2 keys	t	b	1
Left down diagonal	t	f	1
Right down diagonal	t	h	1
Incorrect hit	t	o	2
Immediate left	t	r	2
Immediate right	t	y	2
Immediate right	u	i	2
Right 2 keys	u	o	1
Left down diagonal	u	h	2
Immediate down	u	j	3
Immediate right	w	e	1
Incorrect hit	y	e	1
Left 2 keys	y	r	1
Immediate right	y	u	1
Total number of errors			105

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