Tactile Rendering of Digital Buttons and Shapes on Touchscreens Using Novel Surface Haptics Technologies

by

Bushra Sadia

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Koç University

Graduate School of Sciences and Engineering

This is to certify that I have examined this copy of a doctoral dissertation by

Bushra Sadia

and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
examining committee have been made.

Committee Members:

Prof. Çağatay Başdoğan, Advisor

Assoc. Prof. Tevfik Metin Sezgin, Co-Advisor

Assist. Prof. Didem Unat

Assist. Prof. Mehmet Ayyildiz

Prof. Roope Raisamo

Prof. Katherine J. Kuchenbecker

Date: ______________________

To my husband and parents,

for their infinite love and support.

ABSTRACT

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Doctor of Philosophy in Computational Sciences and Engineering

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Touchscreens are integrated in every aspect of our daily life as mobile phones, ATMs, tablets, vending machines, and car navigation systems. These screens provide an intuitive interface for touch interactions with no or limited haptic feedback. As a result, eye-free interaction is nearly impossible and users have to rely on visual and audio feedback to perform a task, which reduces the users' performance and experience. However, with the recent advances in surface haptics technologies, it is now becoming possible to generate complex tactile effects on touchscreens and enhance the user interactions by displaying more sophisticated haptic feedback.

The overall goal of this thesis is to understand how to render realistic tactile buttons and shapes on touchscreens using novel surface haptics technologies. In this regard, the first part of the thesis focuses on creating vibrotactile feedback on a touchscreen that simulates the feeling of physical buttons using piezo actuators attached to the screen. For that purpose, we first recorded and analyzed the force, acceleration, and voltage data from twelve participants interacting with three different physical buttons: latch, toggle, and push buttons. Then, a button-specific vibrotactile stimulus was generated for each button based on the recorded data. Our results showed that participants were able to match the three digital buttons with their physical counterparts with a success rate of 83%. In addition, participants rated the degree of their subjective feelings using seven adjective pairs for all the physical and digital buttons investigated in this study. Our results showed that there exist at least three adjective pairs for which participants have rated two out of three digital buttons similar to their physical counterparts.

In the second part, we investigated the recognition rate and time of five tactile shapes (i.e., triangle, square, pentagon, hexagon, and octagon) rendered by electrovi-

bration on a touchscreen using three different methods and displayed in prototypical orientations and non-prototypical orientations (i.e., 15 degrees CW and CCW to the prototypical orientation). The results showed that the correct recognition rate of the shapes was higher when the haptically active area (area where electrovibration was on) was larger. However, as the number of edges increased, the recognition time increased and the recognition rate dropped significantly, arriving to a value slightly higher than the chance rate of 20% for non-prototypical octagon. Moreover, the recognition time for inside rendering condition was significantly shorter as compared to edge and outside rendering conditions and edge rendering condition led to the longest recognition time. Our analyses of exploration strategies revealed that participants first used global scanning to extract the coarse features of the displayed shapes, and then they applied local scanning to identify finer details, but needed another global scan for final confirmation in the case of non-prototypical shapes. We also observed that it was highly difficult to follow the edges of shapes and recognize shapes with more than five edges under electrovibration when a single finger was used for exploration.

The results of these studies show that richer haptic stimuli is necessary for realistic rendering of digital buttons and shapes on touchscreens. For example, lack of kinesthetic feedback in rendering buttons and displaying haptic feedback in tangential direction only in rendering shapes adversely affected the perception of the participants in our study. These results are considered as a starting point for the development of tactile stimuli, haptically improved user interfaces, and touchscreen applications. These findings can also provide some guidance to haptic interface designers in developing techniques for efficient and effective interaction with graphical elements on touchscreens.

ÖZETÇE

Yeni Yüzey Dokunsal Geribildirim Teknolojilerini Kullanarak Dokunmatik Ekranlarda Dijital Düğmelerin ve Şekillerin Dokunsal Oluşturulması

Bushra Sadia
Hesaplamalı Bilimler ve Mühendislik, Doktora
Eylül 21, 2021

Dokunmatik ekranlar, cep telefonları, ATM'ler, tabletler, otomatlar ve araç navigasyon sistemleri gibi günlük hayatımızın her alanına entegre edilmiştir. Bu ekranlar, dokunsal geri bildirim içermeyen veya sınırlı dokunsal geri bildirim ile dokunmatik etkileşimler için sezgisel bir arayüz sağlar. Sonuç olarak, göz olmadan etkileşim neredeyse imkansızdır ve kullanıcıların bir görevi gerçekleştirmek için görsel ve sesli geri bildirime güvenmeleri gerekir, bu da kullanıcıların performansını ve deneyimini azaltır. Bununla birlikte, yüzey haptik teknolojilerindeki son gelişmelerle, artık dokunmatik ekranlarda karmaşık dokunsal efektler oluşturmak ve daha sofistike dokunsal geri bildirim görüntüleyerek kullanıcı etkileşimlerini geliştirmek mümkün hale geliyor.

Bu tezin genel amacı, yeni yüzey haptikleri teknolojileri kullanılarak dokunmatik ekranlarda gerçekçi dokunsal düğmelerin ve şekillerin nasıl oluşturulacağını anlamaktır. Bu bağlamda, tezin ilk kısmı, ekrana bağlı piezo aktüatörleri kullanarak fiziksel düğmelerin hissini simüle eden bir dokunmatik ekran üzerinde vibrotaktil geri bildirim oluşturmaya odaklanmaktadır. Bu amaçla, önce üç farklı fiziksel düğmeyle etkileşime giren on iki katılımcının kuvvet, ivme ve voltaj verilerini kaydettik ve analiz ettik: mandal, geçiş ve basma düğmeleri. Daha sonra, kaydedilen verilere dayalı olarak her düğme için düğmeye özel bir titreşimli uyaran üretildi. Sonuçlarımız, katılımcıların üç dijital düğmeyi %83'lük bir başarı oranıyla fiziksel benzerleriyle eşleştirebildiklerini gösterdi. Ek olarak, katılımcılar bu çalışmada incelenen tüm fiziksel ve dijital düğmeler için yedi sıfat çifti kullanarak öznel duygularının derecesini derecelendirdiler. Sonuçlarımız, katılımcıların üç dijital düğmeden ikisini fiziksel karşılıklarına benzer şekilde derecelendirdiği en az üç sıfat çifti olduğunu

gösterdi.

İkinci bölümde, dokunmatik ekranda elektrovibrasyon kullanarak, üç farklı dokunsal göreselleştirme yöntemi ile (iç, dış, kenar) oluşturulan ve prototip ve prototip olmayan yönlerde görüntülenen beş dokunsal şeklin (yani üçgen, kare, beşgen, altıgen ve sekizgen) tanıma oranı ve süresi araştırıldı. Sonuçlar, haptik olarak aktif alan (elektrotitreşimin açık olduğu alan) daha büyük olduğunda şekillerin doğru tanıma oranının daha yüksek olduğunu gösterdi. Bununla birlikte, kenar sayısı arttıkça, tanıma süresi arttı ve tanıma oranı önemli ölçüde düştü, örenğin prototip olmayan sekizgen için %20 şans oranından biraz daha yüksek bir değere ulaştı. Ayrıca, iç görselleştirme koşulu için tanıma süresi, kenar ve dış görselleştirme koşullarına kıyasla önemli ölçüde daha kısaydı ve kenar görselleştirme koşulu, en uzun tanıma süresine yol açtı. Dokunsal keşif stratejileri analizlerimiz, katılımcıların önce görüntülenen şekillerin kaba özelliklerini çıkarmak için global taramayı kullandıklarını ve daha sonra daha ince ayrıntıları belirlemek için yerel tarama uyguladıklarını, ancak prototip olmayan şekiller durumunda nihai onay için başka bir global taramaya ihtiyaç duyduklarını ortaya koydu. Keşif için tek bir parmak kullanıldığında, elektrovibrasyon altında şekillerin kenarlarını takip etmenin ve beşten fazla kenarı olan şekilleri tanımanın oldukça zor olduğunu gözlemledik.

Bu çalışmaların sonuçları, dokunmatik ekranlarda dijital düğmelerin ve şekillerin gerçekçi bir şekilde oluşturulması için daha zengin dokunsal uyaranların gerekli olduğunu göstermektedir. Örneğin, düğmelerin oluşturulmasında kinestetik geribildirimin olmaması ve şekillerin oluşturulmasında dokunsal geribildirimin sadece teğetsel yönde olması, çalışmamızdaki katılımcıların algısını olumsuz etkilemiştir. Bu bulgular, dokunmatik ekranlardaki grafik öğelerle verimli ve etkili dokunsal etkileşim için teknikler geliştirmede dokunsal arayüz tasarımcılarına rehberlik edebilir.

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ABBREVIATIONS

ANOVA	Analysis of variancce
ACC	Accuracy
3AFC	Three-alternative forced choice
CCW	Counter clockwise
CW	Clockwise
DAQ	Data aquisition
DTW	Dynamic time warping
ERM	Eccentric rotating mass
FN	False negative
FP	False positive
FRF	Frequency response function
GGM	Grand geometric mean
GM_p	Geometric mean of each participant
GUI	Graphical user interface
IR	Infrared
LCD	Liquid-crystal display
LDV	Laser doppler vibrometer
LED	Light-emitting diode
MANOVA	Multivariate analysis of variance
PREC	Precision
SN	Sensitivity
TP	True positive
TN	True negative

Chapter 1

INTRODUCTION

Over the last decades, technological advancements have revolutionized the way we access information and have enabled us to interact with digital objects using touch. There is already an extensive adoption of touch-input surfaces in our daily devices, such as in mobile phones, tablets, navigation interfaces in cars, human machine interfaces in factories, and entertainment systems in homes. It is also anticipated that many physical surfaces such as refrigerator doors, bathroom mirrors, tabletops, and home windows will be converted to touch-input surfaces in the future. Although existing touch-enabled devices provide visual and audio feedback to the users, tactile feedback is either missing or highly limited, which is essential for natural and intuitive interaction.

Haptics offers a new form of engagement with such surfaces by presenting compelling touch experiences. The interest in touch surfaces displaying tactile feedback to the user has risen over the last decade, and a new research field called surface haptics has emerged. Researchers have presented various ways of rebuilding the feel of natural sensations and interactions by displaying programmable haptic effects in the form of vibrations, pulses, and variable friction forces to the fingertips of users. Surface haptics has many potential and exciting applications in various domains (see a review of surface haptics in [Basdogan et al., 2020]). In applications targeted to general users, surface haptics can enrich the user experience by providing additional sensory feedback through haptic channel (e.g., feeling more frictional resistance while dragging a larger size folder on a touchscreen). Users can benefit from these sensory augmentations especially when they cannot focus their full attention on digital information displayed through visual channel (e.g., controlling the digital buttons of a navigation interface with the help of tactile feedback while driving a car). On the other hand, users with visual impairments can take advantage of surface haptics to perceive the information provided as visual data such as pictures, diagrams, plots, charts, graphs, maps, networks, and tables.

The most common actuation methods for displaying tactile feedback on touch surfaces are vibrotactile, ultrasonic, and electrostatic. In vibrotactile actuation, a vibration signal at a frequency that is detectable by the fingertip of a user (typically below 500 Hz) is displayed through a touch surface [Chen et al., 2011, Choi and Kuchenbecker, 2012, Kim et al., 2021]. The simplest and most prevalent example for this technology is the touch surface of a mobile phone, which is typically actuated by different vibrotactile actuators to create various haptics effects such as informing the user about the incoming calls and providing conformation for button clicks. In ultrasonic actuation, the touch surface is vibrated mechanically at an ultrasonic resonance frequency, which produces a thin layer of air gap between the user's finger and the surface [Watanabe and Fukui, 1995, Biet et al., 2007, Chubb et al., 2010, Saleem et al., 2018], resulting in a reduction in sliding friction. In order to render a desired tactile effect, the vibration amplitude on the touch surface can be modulated accordingly. Electrostatic actuation also modulates the friction between the user's fingertip and a touch surface. Unlike other actuation technologies, there is no mechanical vibration on a touch surface, but an electrostatic attraction force is generated between the surface and finger when an AC voltage is applied to the conductive layer of a capacitive touchscreen. This additional force in the normal direction increases the frictional force between the finger and the touch surface in the tangential direction (called as the electrovibration effect), which can be modulated by altering the amplitude, frequency, and waveform of the applied voltage [Bau et al., 2010, Vardar et al., 2016, Emgin et al., 2018].

These actuation methods can display a variety of tactile stimuli to the users during their interaction with touch surfaces. For instance, various types of vibration motors such as eccentric rotating mass, linear resonant actuators, and voice coil actuators, and piezoelectric actuators are utilized to create tactile feeling of digital buttons on touchscreens [Nashel and Razzaque, 2003, Brewster et al., 2007, Hoggan et al., 2008a, Hoggan et al., 2008b, Tashiro et al., 2009, Pakkanen et al., 2010, Park et al., 2011, Chen et al., 2011, Lylykangas et al., 2011, Kim et al., 2012, Kim and Tan, 2014, Wu and Smith, 2015, Ma et al., 2015, Saleem et al., 2017]. On the other hand, friction modulation techniques are mostly used to render 2D tactile graphics and 3D geometrical shapes [Israr et al., 2012, Kim et al., 2013, Mullenbach et al., 2014, Osgouei et al., 2016, Osgouei et al., 2017, Bateman et al., 2018, Klatzky et al., 2019, Tomita et al., 2019], realistic virtual textures [Messaoud et al., 2016, Ilkhani et al., 2017, Osgouei et al., 2018, Jiao et al., 2018], virtual edges [Chubb et al., 2010], and digital widgets such as virtual knobs [Emgin et al., 2018] on touchscreens. This thesis focuses on two actuation methods; vibrotactile actuation using piezoelectric actuators for rendering of digital buttons and electrovibration for rendering of geometrical shapes on touchscreen.

1.1 Problem Definition and Approach

Touchscreens are an integral part of our mobile phones, tablets, laptops, ATMs, tabletops, vending machines, electronic kiosks, and car navigation systems. These interactive screens have replaced the physical controls with the digital ones. These digital controls are displayed on a smooth touch surface and cannot provide haptic feedback similar to the conventional physical controls. Users have to rely on their visual and auditory channels when interacting with these digital controls, which leads to overburden their visual and auditory channels and their haptic channel remains under utilized. The most basic interaction method on these touchscreens is pressing a digital button to perform some specific tasks such as send an email, write a message, dial a phone number, or type a digital keyword to search the Web. When a digital button is activated by pressing on these touchscreens, typically visual (such as change of appearance, shape, and color) or audio (such as button click sound) feedback or both are displayed to inform users of their actions. Compared to vision and sound, haptics has been utilized less as sensory feedback for digital buttons [Lee and Zhai, 2009]. Also, the lack of sophisticated tactile feedback in these digital buttons results in a decrease in user experience quality and even task performance [Banter, 2010, Kaaresoja et al., 2014, Kaaresoja, 2016]. Although researchers have utilized various electromechanical actuators to create the tactile feeling of digital buttons on touchscreens [Nashel and Razzaque, 2003, Brewster et al., 2007, Hoggan et al., 2008a, Hoggan et al., 2008b, Park et al., 2011, Pakkanen et al., 2010, Tashiro et al., 2009, Chen et al., 2011, Lylykangas et al., 2011, Kim et al., 2012, Kim and Tan, 2014, Wu and Smith, 2015, Ma et al., 2015, Saleem et al., 2017], they have mainly focused on displaying "pleasant" button click sensations using vibration cues, but not the realistic feeling. Therefore, creating vibrotactile stimuli for digital buttons with distinct features based on the measured data originating from their mechanical counterparts has not been considered before. Researchers have mainly used this approach for realistic rendering of viscoelastic materials using a force feedback device [Höver et al., 2010], realistic rendering of textures by a voice coil actuator [Romano and Kuchenbecker, 2012, Culbertson et al., 2014a, Culbertson et al., 2014b], and electrostatic actuation on touchscreens [Ilkhani et al., 2017, Osgouei et al., 2018].

Another interaction method is the exploration of tactile graphics on these touch surfaces. Users employ some intuitive strategies to explore tactile graphics on touch surfaces. Not only the users' exploration strategies, but also tactile data's complexity and tactile rendering methods affect the haptic perception of the users. Therefore, it is critical to understand how users perceive tactile graphics displayed to them on these touch surfaces and what exploratory procedures are followed to perceive them. Although, earlier research has investigated this topic for vibrotactile feedback alone [Toennies et al., 2011, Giudice et al., 2012, Awada et al., 2013, Palani and Giudice, 2014, Tennison and Gorlewicz, 2016, Tekli et al., 2018] and also the combination with auditory feedback [Poppinga et al., 2011, Giudice et al., 2012, Tennison and Gorlewicz, 2019, Gorlewicz et al., 2020], to our knowledge, no previous work has investigated it for electrovibration in depth. In comparison to vibrotactile feedback, which mainly stimulates the finger in the normal direction, electrovibration modulates the sliding friction between the finger and the touch surface in the tangential direction. Hence, one can anticipate that haptic exploratory procedures followed by the users for virtual tactile graphics under electrovibration would be different from those employed for real tactile graphics and also the virtual ones rendered by vibrotactile actuators.

The first aim of this thesis is to investigate how to create tactile feedback that simulates the feelings of physical buttons on a touchscreen. For that purpose, we focus on three different types of physical buttons to display their digital counterparts on a touchscreen: *Latch Button*, *Toggle Button*, and *Push Button*. We recorded force, acceleration, and voltage data for activation state from those buttons while twelve participants were pressing on them. Our experimental data reveals that these three buttons have distinct features in terms of (a) the magnitude of normal force required for activation, (b) the activation state with respect to the instant of voltage change, and (c) the resulting mechanical vibrations (acceleration) of the button when pressed. We mapped the recorded acceleration signal of each physical button to a voltage signal that actuates the piezo patches of an interactive multi-touch table [Emgin et al., 2018] for displaying their digital counterparts on its touch surface. We then conducted two experimental studies to investigate how these digital buttons were perceived by the user. Our first study was a matching experiment, where twenty participants participated in a three-alternative forced choice (3AFC) experiment to match the digital buttons with their physical counterparts. Our second study investigated the perceptual feelings arising from pressing three physical and digital buttons. A very recent study by [Liu et al., 2018] investigated the perceptual dimensions associated with manual key clicks. However, it was limited to only different types of push buttons. In our second experiment, we first collected a set of adjectives from the participants that describes their perceptual feelings of pressing three physical buttons. Then, participants rated the degree of feelings associated with each adjective for the physical and digital buttons investigated in this study.

In the second part of the thesis, we conducted experimental studies to investigate the tactile exploration strategies followed by the users for basic geometrical shapes displayed by electrovibration on a touchscreen. We first investigated the effects of (a) number of edges, (b) rendering conditions, and (c) angular orientation on the recognition rate and time of 2D equilateral tactile shapes to answer the following research question; *How does the size of haptically active area and the complexity of geometry affect the perception of tactile shapes?* Moreover, we evaluated the strategies followed by the participants to explore these shapes by performing spatial and temporal analyses on the recorded data of finger position to tackle the following research question; *What type of exploratory procedures were followed by the participants to perceive tactile shapes?* Spatial analysis was performed quantitatively by using the heat maps generated from participants' finger positions, and temporal analysis was performed qualitatively by tagging videos of finger movements via visual inspection.

1.2 Contribution

In this thesis, we investigated the generation of realistic digital buttons and geometrical shapes on touchscreens using surface haptics technologies. First, we proposed a data-driven approach that includes the recording of force, acceleration, and activation state in terms of voltage from three different physical buttons and rendering them on a vibrotactile display. We evaluated our proposed approach by conducting user studies with twenty participants. The results showed that participants were able to relate digital buttons with their physical counterparts with a success rate of 83%. Moreover, in the perceptual domain, participants were able to match two of the three digital buttons with their physical counterparts on at least three adjective pairs. Our findings showed that it is possible to generate realistic button click sensations on touchscreens by utilizing data-driven approach. Afterward, the investigation of rendering of geometrical shapes with different number of edges, rendering conditions, and orientation on touchscreens revealed that recognition rate is inversely proportional, and recognition time is directly proportional to the complexity of the shapes. The size of the haptically active area also affects the perception of the shapes. The analyses of exploration strategies revealed that participants employed different strategies to explore prototypical and non-prototypical shapes. For prototypical shapes, they started with global-scanning to get the overall idea of the rendered shape, followed by local-scanning to identify the shape by counting the edges. On the other hand, for non-prototypical shapes, they performed an extra global-scanning at the end for the final confirmation of their selected choice for the displayed shape. We also observed that during the exploration of non-prototypical shapes, participants focused on counting the corners. These findings can provide some guidance to haptic interface designers in developing techniques for efficient and effective interaction with tactile graphics displayed by electrovibration.

1.3 Thesis Outline

This thesis is organized into five chapters, including this chapter. In Chapter 2, we first present the relevant literature related to the rendering of digital buttons on touchscreen, and then we discuss the literature related to the exploration of tactile graphics on touch surfaces. Chapter 3 presents the methodology to collect and process data from different physical buttons and generate their digital counterparts to render on a touchscreen. The experimental setup used to render these digital buttons is explained in section 3.2 followed by the two user studies to evaluate our approach. Chapter 4 investigates the exploration strategies employed by the participants to explore tactile graphics on touchscreen under electrovibration. The experimental setup used in this study is elaborated in section 4.1. Two experiments were conducted in this study. The first experiment aims to determine the influence of the number of edges and rendering conditions on the recognition rate and time, and the second experiment investigates the effect of angular perturbation on the recognition rate and time of the tactile shapes displayed by electrovibration on touchscreen. In the end, the key results of this thesis along with the future directions are discussed in Chapter 5.

Chapter 2

BACKGROUND

In this chapter, we first present the related work on rendering of digital buttons on touchscreens. Afterward, we review the strategies employed by the participants to explore tactile graphics on touchscreens.

2.1 Rendering of Digital Buttons on Touchscreens

Researchers have utilized various types of electromechanical actuators, such as voice coils, vibration motors [Fukumoto and Sugimura, 2001, Nashel and Razzaque, 2003, Brewster et al., 2007, Hoggan et al., 2008a, Hoggan et al., 2008b, Park et al., 2011] and piezoelectric actuators [Tashiro et al., 2009, Pakkanen et al., 2010, Chen et al., 2011, Lylykangas et al., 2011, Kim et al., 2012, Kim and Tan, 2014, Wu and Smith, 2015, Ma et al., 2015, Saleem et al., 2017] to display haptic feedback for interactions with digital buttons.

[Fukumoto and Sugimura, 2001] utilized a linear resonant actuator to create a simple click feeling when a user presses a button on a resistive touchscreen. Their results showed that tactile feedback outperformed aural feedback in a simple calculation task, especially in noisy situations. [Nashel and Razzaque, 2003] used vibration motor to add tactile cues to the virtual buttons on touchscreen of mobile devices. They provided low amplitude vibrations to the users when their finger is on a virtual button. They showed that all users were able to differentiate between vibration (finger on a virtual button) and no vibration (finger not on a button) regions. [Hoggan et al., 2008b] investigated the cross-modal congruency between the visual and audio/tactile feedback for digital buttons of mobile touchscreens. They used Eccentric Rotating Mass (ERM) and piezoelectric actuators to create four different vibrotactile stimuli for displaying eight visually different digital buttons in terms of shape, size, and height. Their study revealed that users could successfully relate between the visual and audio/tactile properties of buttons. They also compared a standard touchscreen with the one displaying tactile feedback and concluded that the addition of tactile feedback significantly reduces the errors in finger-based text entry [Hoggan et al., 2008a]. [Koskinen et al., 2008] investigated the characteristics of digital buttons displayed by piezoelectric actuators and vibration motors (ERM) on touchscreens to identify the type of tactile click that is perceived as most pleasant to the finger. They showed that digital buttons with tactile feedback are superior to the ones without tactile feedback, regardless of the technology used to create tactile feedback. Their results also showed that piezoelectric actuators created more pleasant feedback compared with vibration motors.

[Park et al., 2011] focused on displaying tactile feedback on mobile devices when a digital button is pressed on the screen. They presented seventy-two different vibrotactile stimuli to the participants by varying amplitude, duration, carrier signal, envelope function, and type of actuators. These waveforms are analogous to the typical acceleration profiles that are observed during contacts of a pen/stylus with a rigid surface [Okamura et al., 2001], which can be modeled using an exponentially decaying sinusoidal function. They suggested that, for pleasant button clicks, short rise time as well as short duration are preferable. [Chen et al., 2011] designed and evaluated a set of simulated key clicks for key-less mobile devices equipped with piezoelectric actuators. They concluded that key clicks are perceived as "dull" and "crisp" at the stimulation frequency of 125 Hz and 500 Hz, respectively. [Lylykangas et al., 2011] investigated the preference in type of tactile feedback displayed by piezo-actuated digital buttons under different time delays and vibration durations. Their results showed that, it is possible to create either favorable or significantly less favorable button click feedback by varying delay and duration parameters within a relatively short time window. They also concluded that the signal for tactile feedback requires careful design and control of the duration parameter. Haptic feedback can also be displayed during the process of pushing down a button [Kim and Lee, 2013]. This type of feedback mimics the force-displacement curve of a mechanical button to further enhance the perceived realism of a digital button.

In 2015, Apple Inc.[1] introduced Taptic Engine, a tiny motorized actuator that oscillates back and forth, to simulate the physical click on a non-mechanical home button of iPhone using pressure sensitive technology [Apple, 2021]. They integrated capacitive sensors into the backlight of the display. The microscopic changes between the cover glass and backlight are measured whenever a press is detected. The detected pressure is then transmitted to the Taptic Engine and haptic feedback is provided to the user accompanied by an audible tune [Wikipedia, 2021]. The touchscreen with pressure sensitive layer is, however, removed from the latest iPhones due to the technical challenges of implementing an edge-to-edge display. Instead of detecting pressure, tactile feedback is now provided to the users based on how long they hold their finger on a UI element [Wikipedia, 2021].

A button-like click feeling can also be generated via squeeze film effect [Tashiro et al., 2009, Monnoyer et al., 2016, Saleem et al., 2017] by varying friction coefficient between user's finger and touchscreen. [Tashiro et al., 2009] utilized ultrasonic vibration to display the feeling of buckling and restitution events of a mechanical button on a touchscreen. They showed that the perception of button click can be created by reducing friction coefficient between the user's finger and touchscreen. [Monnoyer et al., 2016] showed that key-click feeling can be achieved by sudden release of stress at the fingertip that is accumulated when the surface friction is high. [Saleem et al., 2017] reported that the rate of change in normal friction plays an important role in order to perceive button click sensation on an ultrasonically actuated touch surface.

[1]https://www.apple.com/

2.2 Exploration Strategies on Touchscreens

Researchers have already utilized surface haptics technologies to render tactile graphics on touch surfaces [Israr et al., 2012, Kim et al., 2013, Gorlewicz et al., 2014, Mullenbach et al., 2014, Osgouei et al., 2016, Osgouei et al., 2017, Klatzky et al., 2019]. However, only a few studies investigated the relation between the complexity of tactile data displayed through a touch surface and haptic perception of the users [Gorlewicz et al., 2020, Costes et al., 2020]. The results of these studies showed that the user's haptic channel and memory should not be overloaded to deliver the desired information effectively while displaying sufficient amount of details and utilizing an established rendering methodology are both required to ensure expressiveness and efficiency. [Gorlewicz et al., 2020] reported that users form a mental image of the displayed shape in memory during tactile exploration, and successful recognition depends on effective tactile rendering of vertices, lines, and particular angles of the shape. They also emphasized the importance of reducing the size of white space in applications (i.e., haptically inactive area). They recorded the user's finger position in exploring bar charts and basic geometric shapes and reported how much time is spent on different items. They concluded that appropriate tactile design (i.e., type of shapes and orientations) and suitable rendering approach (e.g., stimulation type, location, and duration) are essential to create successful surface haptics applications.

2.2.1 Tactile Graphics

Tactile graphics play an essential role in the life of visually impaired and blind people. For them, it is the means to access visual information for various purposes such as education, entertainment, and navigation [Wright, 2008, Smith and Smothers, 2012, Grussenmeyer and Folmer, 2017, Ducasse et al., 2018, Vinter et al., 2020]. Tactile graphics is typically displayed in the form of raised surfaces [Kennedy, 1993, Heller et al., 2002, Shiose et al., 2008, Bardot et al., 2017]. It is produced by embossing on non-refreshable media such as plastic sheets, paper, or heat-sensitive swell paper.

However, this approach does not support multimodal interaction, and the graphics, once created, is static and cannot be updated unless completely reproduced. Also, the production requires special equipment and the process is relatively expensive and time-consuming. As alternatives, researchers have utilized force and tactile feedback, and sonification to convey information to blind or visually impaired users and in situations in which the visual channel is highly loaded or ineffective [Griffin, 2001, Paneels and Roberts, 2009, O'Modhrain et al., 2015].

Force feedback devices, coupled with vibratory, verbal, and auditory cues, are utilized to present graphical information to the users [Petrie et al., 2002, Magnuson and Rassmus-Gröhn, 2003, McGookin and Brewster, 2006, Crossan and Brewster, 2008, Yannier et al., 2008]. [Crossan and Brewster, 2008] utilized force feedback enriched with audio cues to guide the user's hand in outlining simple geometric shapes. [Yannier et al., 2008] displayed wind forces through a force feedback device in connection with surface topography in order to educate students about cause and effect relations in climate visualization. Readers are referred to [Paneels and Roberts, 2009] for a detailed review of the approaches implemented by force feedback devices for haptic data visualization. However, force feedback devices are often expensive, bulky, and lack portability, which hinder their usage in daily life.

For those reasons, researchers have focused on creating accessible tactile graphics on touch surfaces such as the touchscreens of mobile devices. The most common actuation approach in this regard is vibrotactile. Low-cost vibration motors embedded in mobile devices have been frequently utilized for this purpose and several studies have already reported that this approach is viable in recognizing non-visual graphics and shapes [Poppinga et al., 2011, Toennies et al., 2011, Giudice et al., 2012, Awada et al., 2013, Palani and Giudice, 2014, Tennison and Gorlewicz, 2016]. However, complex tactile effects cannot be generated by such vibrators since they have a limited frequency bandwidth. Moreover, they vibrate the whole screen and do not provide localized tactile feedback. Although there are a few prototypes demonstrating multi-touch and localized tactile stimulation [Bai and Tsai, 2011, Hudin et al., 2015, Emgin et al., 2018, Dhiab and Hudin, 2020, Hwang et al., 2021], the techniques presented in these studies are not straightforward to implement. To overcome this problem, [Goncu and Marriott, 2011], for instance, proposed a simple but not practical solution. They attached individual vibrators to the fingers of a user to display tactile graphics such as charts and maps.

An alternative approach used by the researchers to render tactile graphics on a touch surface is electrovibration [Bau et al., 2010]. Researchers have utilized electrovibration displays to render 2D tactile graphics and 3D geometrical shapes in the form of height maps [Israr et al., 2012, Kim et al., 2013, Mullenbach et al., 2014, Osgouei et al., 2016, Osgouei et al., 2017, Bateman et al., 2018, Klatzky et al., 2019, Tomita et al., 2019]. Although these displays offer a rich touch experience, there has been insufficient research on the haptic exploratory strategies followed by the users to perceive tactile shapes.

2.2.2 Haptic Exploratory Procedures

In their seminal studies, Lederman and Klatzky [Klatzky et al., 1987, Lederman and Klatzky, 1993] investigated how specific movements lead to extract particular features of the object's weight, texture, hardness, softness, volume, or local shape features. They classified six haptic exploratory procedures, and among those, they identified three for shapes and surface details; *lateral motion* (a repetitive back and forth movement which is mainly associated with exploring textures), *enclosure* (helps to extract the global information about the shape of an object), and *contour following* (helps to extract the exact shape of the object).

Compared to the haptic perception of 3D objects, less number of studies have investigated the exploration strategies for real and virtual tactile shapes and graphics in 2D [Rovira et al., 2011, Vinter et al., 2012, Bara, 2014, Guerreiro et al., 2015, Tennison and Gorlewicz, 2016, Bardot et al., 2017, Tekli et al., 2018, Bahrin et al., 2019, Vinter et al., 2020]. [Rovira et al., 2011] conducted a study with 2D geometrical shapes (simple and composite) in the form of raised patterns to investigate the haptic exploratory procedures by comparing the performances of blind and sighted adolescents in two experiments on mental rotation (similarity judgment and recognition). They reported that blind adolescents outperformed the sighted ones in simple shapes and preferred bi-manual and multi-finger exploration. On the other hand, sighted participants explored the tactile shapes using the contour following procedure with one hand only. [Vinter et al., 2012] compared the type of exploratory procedures employed by three groups of children (blind, children with low vision, and blindfolded sighted) while exploring 2D tactile patterns. Their findings suggested that children with a visual handicap employed bimanual exploration with a greater number of different procedures as compared to their sighted counterparts. They employed strategies like contour following (dynamic edge following using finger movements) and surface sweeping (dynamic and usually repetitive movement of one or more fingers or of the palm over the model's surface) to extract the information of the pattern as a whole and strategies like pinch (holding edges in a pincer grip between the thumb and one or more other finger) and local enclosure (dynamic molding of the fingers to parts of the pattern) to get the information about the local features. [Bara, 2014] conducted a study with visually impaired children to determine how the tactile pictures were explored during joint book reading. Their findings suggested that participants preferred the lateral motion to recognize the shapes in the pictures, and contour following was preferred when finding the pictures' meaning. [Bardot et al., 2017] investigated the role of each hand during the exploration of different raised-lines graphics (drawing, maps, and graphs) by sighted blind-folded and visually impaired participants. They concluded that visually impaired participants were faster than blindfolded participants because they focused on exploring the salient areas of the displayed graphics using bimanual exploration. [Bahrin et al., 2019] developed a fingertip tracking system to investigate the exploration strategies employed by blind and visually impaired participants while exploring tactile graphics. The analysis of the collected data showed that participants employed the contour following and the lateral motion strategies only. [Vinter et al., 2020] investigated the role played by the exploratory procedures employed by the children (sighted and visually impaired) to correctly identify and name the tactile images when the experimental settings were designed similar to their natural reading conditions. Their results showed that, regardless of the visual status of the children, they were successful in correctly identifying and naming the explored image when they used appropriate exploratory procedures.

In comparison to the studies on real tactile graphics, there are less number of studies investigating the haptic exploratory procedures employed for virtual tactile graphics. [Tennison and Gorlewicz, 2016] investigated the exploratory procedures utilized by the participants to correctly identify the basic tactile shapes displayed by vibration on a touchscreen. They rendered three shapes (triangle, square and pentagon) in small and large sizes on the touch surface of a tablet using its built-in actuators. Vibrotactile feedback was displayed inside the shapes while stronger vibrations were provided to the participants at the edges. They reported that slow and deliberate exploration movements were preferred by the participants as a starting strategy until they became aware of the key features of the displayed graphics. They observed that some participants scanned the screen horizontally to identify the tactile shape in general and some circled around the corners to find nearby edges in particular. [Tekli et al., 2018] investigated how blind users utilize vibrotactile feedback displayed through a touchscreen to recognize simple shapes and graphics. They concluded that participants followed non-traditional haptic exploration strategies such as navigating the screen from left to right horizontally and then from top to bottom vertically to recognize the displayed item on the touchscreen. [Bateman et al., 2018] investigated whether the user could locate a haptic point displayed using textures on a touchscreen within a specified time. Their results showed that participants correctly found a haptic point with an average time of approximately 15 seconds. Their investigation of the user interaction patterns revealed that participants either used a systematic approach or a rapid exploration of a touchscreen to find the haptic point. [Tennison and Gorlewicz, 2019] conducted experiments with visually impaired participants to investigate how they explore virtual line profiles displayed on a touchscreen using auditory and vibratory feedback. Their results suggested that vibrating lines were preferred over auditory lines. Furthermore, participants employed similar haptic exploratory strategies to recognize the lines: zigzagging on a line to follow its profile or circling around the intersection points to determine the orientation of intersecting lines.

Chapter 3

DATA DRIVEN VIBROTACTILE RENDERING OF DIGITAL BUTTONS ON TOUCHSCREENS

Summary

In this chapter[1], we focus on creating vibrotactile feedback on a touchscreen that simulates the feeling of physical buttons using piezoelectric actuators. For that purpose, we first recorded and analyzed the force, acceleration, and voltage data from twelve participants interacting with three different physical buttons: latch, toggle, and push buttons. Then, a button-specific vibrotactile stimulus was generated for each button based on the recorded data. Finally, we conducted a three-alternative forced choice (3AFC) experiment with twenty participants to explore whether the resultant stimulus is distinct and realistic. In our experiment, participants were able to match the three digital buttons with their physical counterparts with a success rate of 83%. In addition, we harvested seven adjective pairs from the participants expressing their perceptual feeling of pressing the physical buttons. All twenty participants rated the degree of their subjective feelings associated with each adjective for all the physical and digital buttons investigated in this study. Our statistical analysis showed that there exist at least three adjective pairs for which participants have rated two out of three digital buttons similar to their physical counterparts.

[1]This work is published in the International Journal of Human Computer Studies [Sadia et al., 2020].

3.1 Categories of Mechanical Buttons

Mechanical buttons and switches are designed to enable or disable current flow in electric circuits. A button must be triggered by an external force to change its state, which can be achieved by different hand gestures (pushing, rotating, sliding, rocking, pulling). The response of each button depends on its unique properties, and accordingly, buttons can be grouped under two main categories (Figure 3.1) [Lindblom, 2013]:

(a) Maintained buttons/switches stay in one state until they are triggered. Toggle, rotary, latch, and slide buttons are examples of maintained buttons.

(b) Momentary buttons/switches stay active as long as pressure is maintained on the switch. Examples of momentary buttons/switches include push buttons and joysticks.

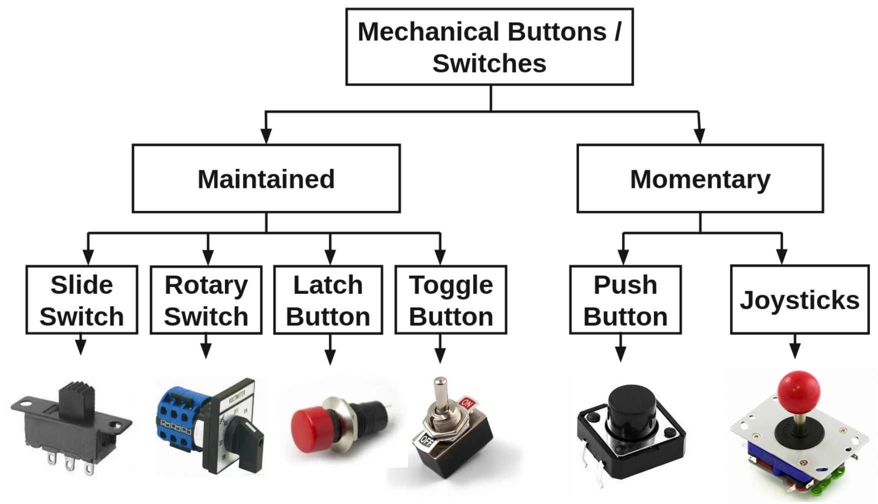


Figure 3.1: Physical buttons/switches can be divided into two main groups. Our study utilizes *Latch Button* and *Toggle Button* from maintained group, and *Push Button* from momentary group.

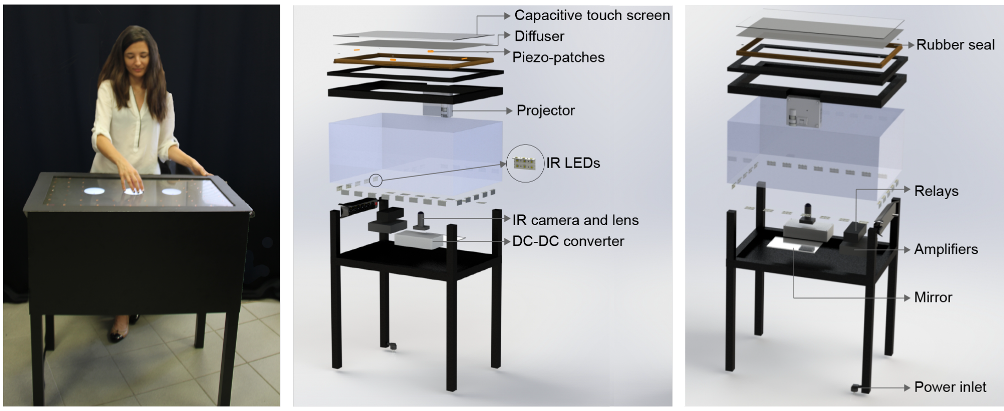
We chose three buttons that we interact frequently in our daily lives: two maintained buttons (*Latch Button* and light button as *Toggle Button*), and one momentary button (*Push Button*) (Figure. 3.2). The acceleration profile (mechanical vibrations that occur when a physical button is pressed) of buckling (pressing a button) and restitution (releasing a button) events are very similar, but they occur in opposite directions [Tashiro et al., 2009]. For rendering purpose, we focus only on the buckling event of these three buttons.

Figure 3.2: Physical buttons used during data collection and in our second experiment: *Latch Button* (1), *Toggle Button* (2), and *Push Button* (3).

3.2 Experimental Setup

We used a custom designed tabletop, HapTable as shown in Figure 3.3, that registers and recognizes touch gestures using rear diffused illumination [Müller-Tomfelde, 2010] and is capable of providing appropriate visual and haptic feedback for the recognized gestures [Emgin et al., 2018].

The interaction surface of HapTable is evenly illuminated with wide angle infrared LEDs (50-Module IR Kit, Environmental Lights). When a user touches this surface, light is reflected from contact points and captured by an infrared camera



(a) (b) (c)

Figure 3.3: User performing a task on HapTable to interact with a digital scene while receiving suitable haptic feedback. The hardware components of HapTable are shown in (b) rear and (c) front views. This image is taken from [Emgin et al., 2018].

(Eye 3, PlayStation). In this study, we added an additional infrared camera (Eye 3, PlayStation) underneath the touch surface at a shorter distance to the interaction surface in order to capture higher-resolution images of the finger contact area as the user presses a digital button.

To generate mechanical vibrations on the surface, HapTable uses a sound card, a high voltage amplifier (E413.D2, Physik Instrumente, Gain: 50), and a solid state relay (Yocto - MaxiCoupler, Yoctopuce). The sound card generates haptic signals, which are amplified by the high voltage amplifier and sent to the solid state relay. The outputs of the solid state relay are connected to individual piezo patches, which can be actuated in less than ten milliseconds. In order to obtain the vibrational characteristics of the touch surface of HapTable, a linear sine sweep voltage signal, varying in frequency from 0 to 625 Hz, was applied to piezo patches using a signal generator. Then, a Laser Doppler Vibrometer (LDV, PDV-100, Polytec) was used to measure the out-of-plane vibrations at 84 grid points on the touch surface, and a signal analyzer (NetDB, 01dB-Metravib) was used to record and analyze these signals. We constructed five vibration maps of the touch surface for each actuation configuration of piezo actuators: when each piezo actuator was excited individually (PA, PB, PC, and PD), and when all piezo actuators were excited together. For further details on vibration maps, readers are referred to [Emgin et al., 2018].

The vibration maps generated for these five cases revealed that the highest vibration amplitude with the largest area of interaction was achieved at a resonance frequency of 263.5 Hz using piezo patch A (PA) at the region shown in Figure 3.4. This resonance frequency is desirable for our application since human tactile sensitivity to vibrotactile stimulus is highest around 250Hz [Jones and Sarter, 2008].

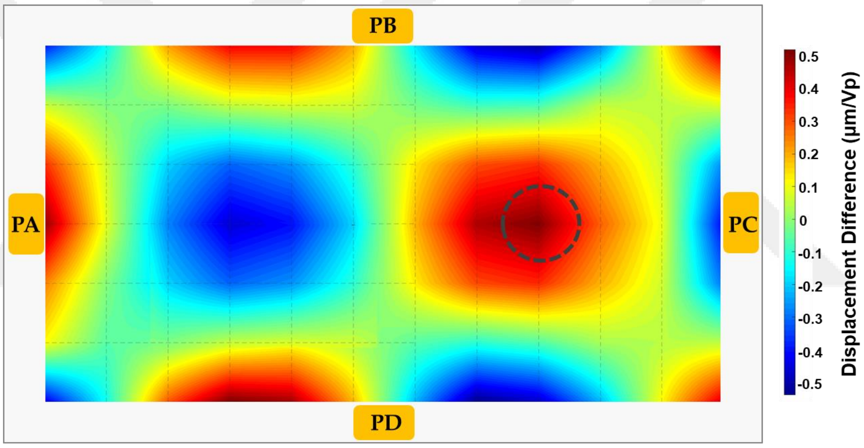


Figure 3.4: Vibration map of the touch surface when piezo patch A (PA) is excited at 263.5 Hz. The digital buttons are rendered at the center of dashed circle.

3.3 Data Collection

To measure the force applied by the user on each physical button, its vertical acceleration, and activation state in the form of a step change in voltage, we built a box enclosing all three buttons (Figure 3.5). A three-axis accelerometer (ADXL 335, Analog Devices Inc.) was attached on top of each button to measure its vertical acceleration and a force sensor (Mini40, ATI Industrial Automation) was placed beneath the box to measure the normal force applied by the user. Two data acquisition cards (PCI-6034E and PCI-6321E, National Instruments) were used to record the force, acceleration, and voltage data simultaneously at 5K samples per seconds. The box was immobilized on a rigid table to reduce the electrical noise due to cabling and undesired external vibrations.

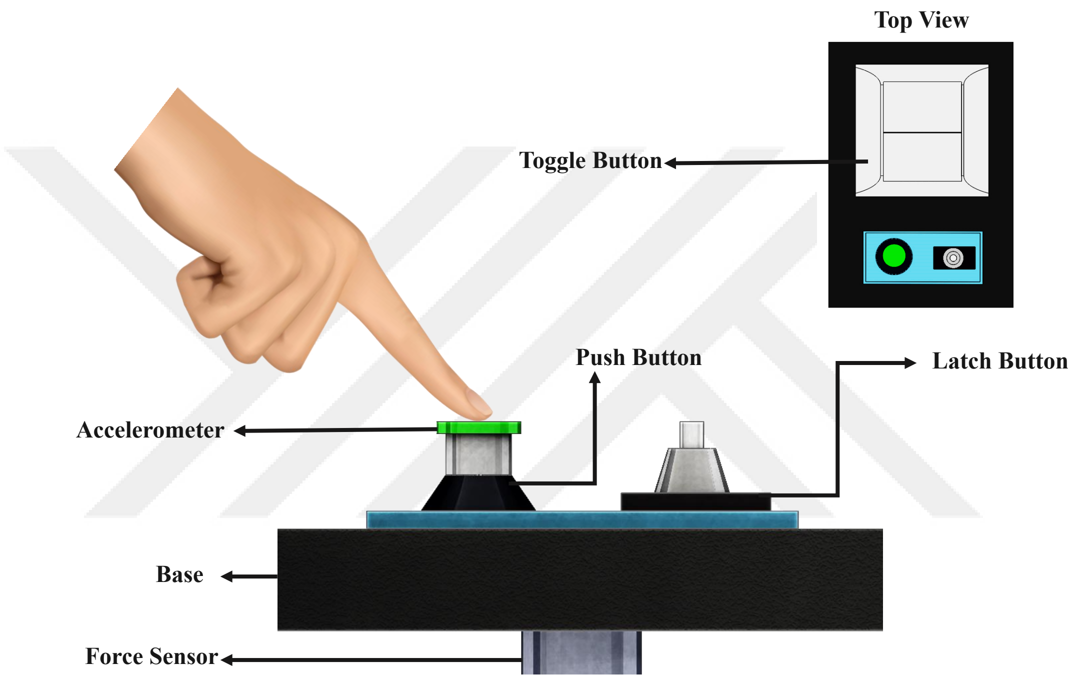


Figure 3.5: Illustration of the experimental setup used for data collection.

Twelve participants (eight males and four females with an average age of 31.12 ± 5.82 years), participated in the data collection experiment. Each participant read, and then signed a consent form approved by the Ethical Committee for Human Participants of the Koç University before the experiment. Participants were asked to press each button ten times using their index finger. During this interaction, we recorded the force applied to button, button's acceleration, and activation state in the form of a step change in the voltage signal. Collecting experimental data from each participant took approximately fifteen minutes.

3.4 Data Processing

Before processing the accelerometer data, we applied a high pass filter with a cutoff frequency of 10 Hz to eliminate an undesired influence of gravitational forces, sensor drift, and user's hand movements [Romano and Kuchenbecker, 2012]. Then, we applied dynamic time warping (DTW) algorithm [Berndt and Clifford, 1994] to the acceleration signals to find a representative signal for each button. This algorithm aligns two time-dependent signals by minimizing the total distance between them. The flowchart used for collecting and processing of acceleration data is shown in Figure 3.6.

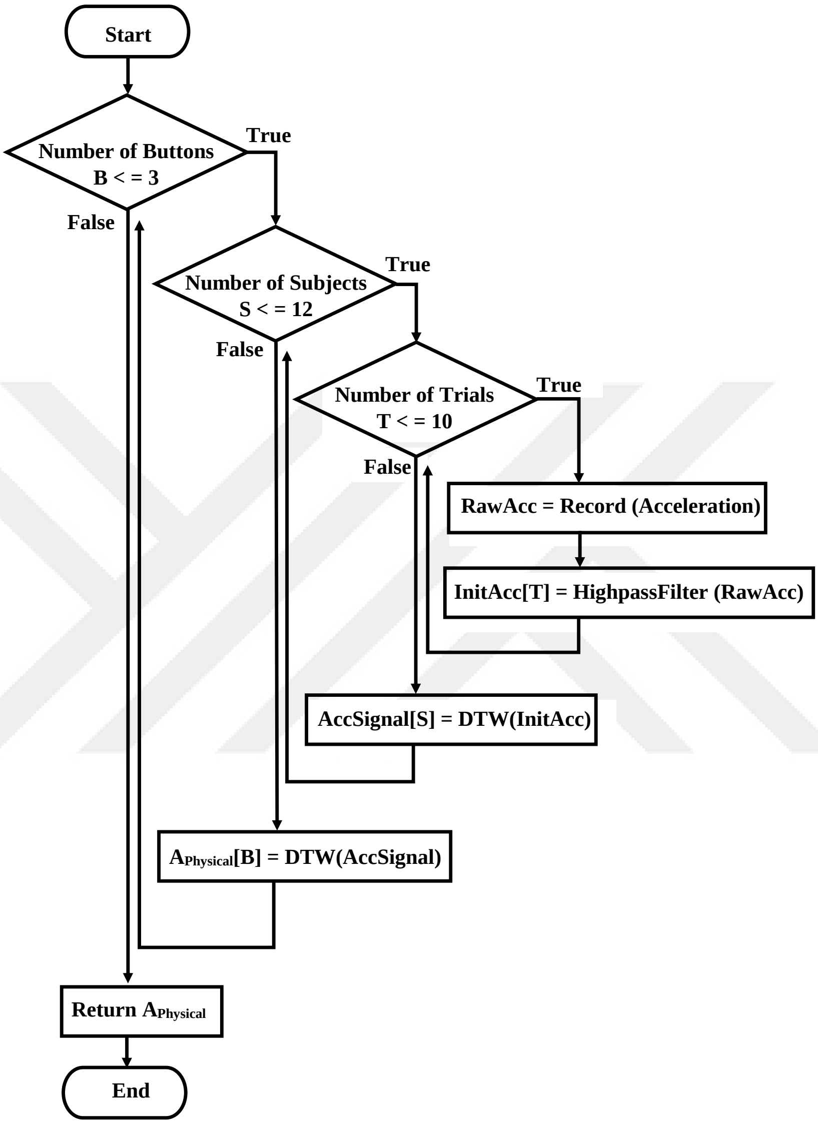


Figure 3.6: Flowchart showing the steps involved in collecting and processing acceleration data. In this chart, **RawAcc** is the recorded acceleration, **InitAcc** is the filtered acceleration, **AccSignal** is the representative signal of a subject and $A_{physical}$ is an array containing the representative acceleration signal of all three physical buttons.

Typical acceleration, force, and activation state profiles recorded from each physical button and the power spectral densities of acceleration signals obtained by Fast-Fourier transform are shown in Figure 3.7. As shown in Figure 3.7, the measured acceleration signals have distinct forms in the frequency domain. Figure 3.8 reports the magnitude of the force applied by each participant to activate each physical button. Figure 3.8 also shows that the participants applied the largest force to activate *Latch Button* while *Toggle Button* required the smallest amount of force to activate.

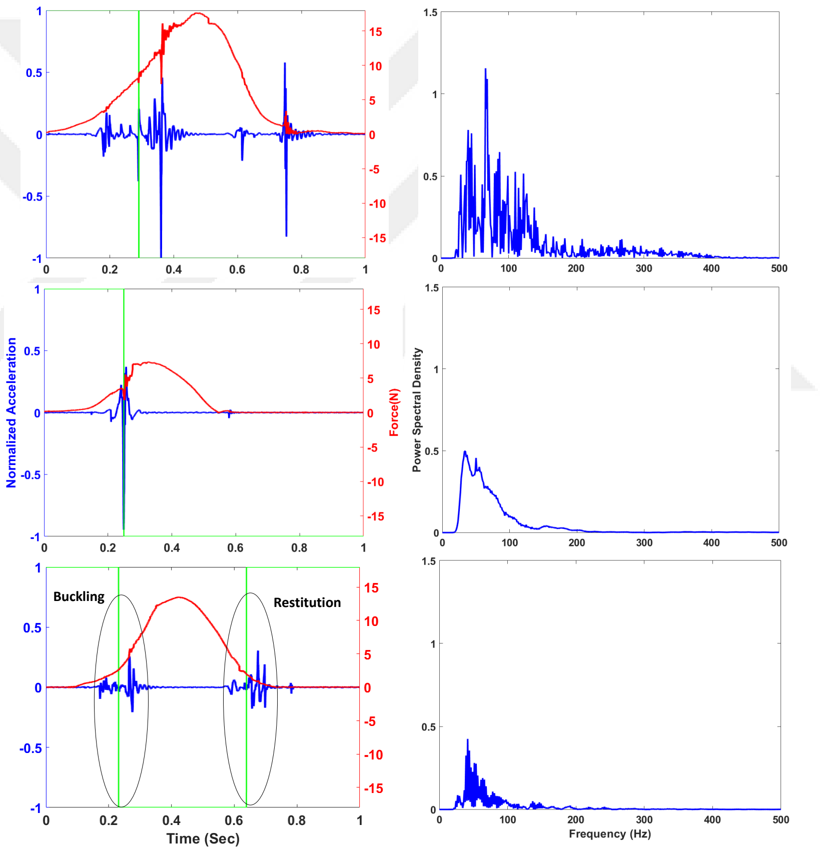


Figure 3.7: Normalized acceleration (blue), force (red), and activation state (green) are shown for *Latch Button* (top), *Toggle Button* (middle), and *Push Button* (bottom) along with the frequency spectrum of the acceleration signals on the right column. The buckling event is shown for *Latch* and *Toggle Buttons* while both events are shown for *Push Button* since it is a momentary type of button.

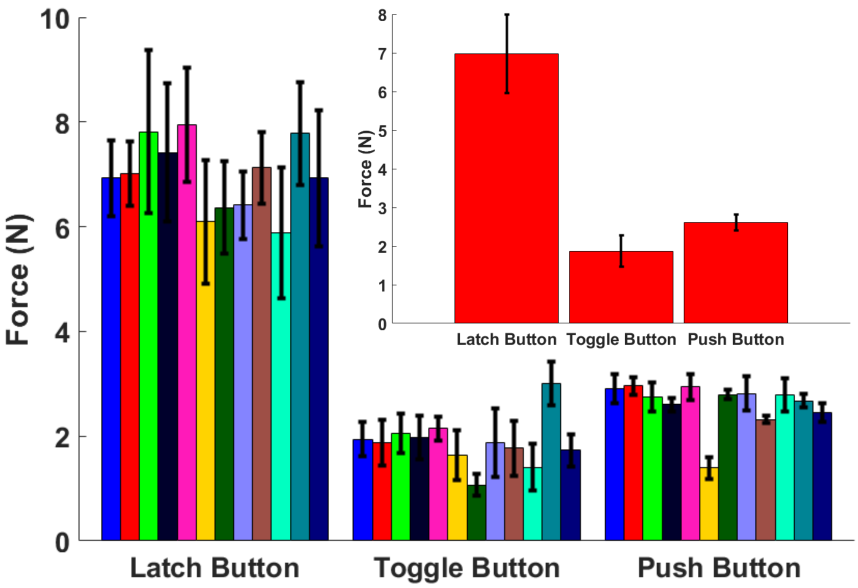


Figure 3.8: Mean and standard deviation of force magnitudes for each participant and all together (upper right). The force data was acquired at the instant of button activation.

In order to construct a vibrotactile waveform for each digital button, we performed amplitude modulation on the acceleration signal recorded from its physical counterpart with the resonant frequency of the touch surface of HapTable (263.5 Hz) using Equation 3.1:

$$A_{digital,i}(t) = A_{physical,i}(t)\sin(2\pi f_c t) \tag{3.1}$$

where i represents the button type, $A_{physical,i}(t)$, and $A_{digital,i}(t)$ are the recorded and synthesized acceleration signals of each button and f_c is the carrier frequency (263.5 Hz).

3.5 Transfer Function Estimation

In order to preserve the spectrum of synthesized waveform $A_{digital}(t)$, we estimated the transfer function between the voltage applied to the piezo patches and the acceleration generated on the touch surface of HapTable using the Frequency Response Function (FRF) recorded for piezo patch A (PA) between the voltage and vibration amplitude, at the point where the digital buttons are displayed to the user (Figure 3.4). We differentiated the FRF twice to get the acceleration/voltage, which was originally measured in the form of displacement/voltage. We then inverted the FRF (voltage/acceleration) and fit a transfer function using `"tfest"` function of MATLAB. Finally, we inputted this transfer function and the synthesized acceleration signal $A_{digital,i}(t)$ to `"lsim"` function of MATLAB to obtain the actuation voltage signal. The voltage signals obtained by this method for all digital buttons are shown in Figure 3.9.

We applied the voltage signals to the piezo patch A (PA in Figure 3.4) and measured the corresponding vibrational velocities at the interaction point on the touch surface (where the digital buttons are displayed to the participant) by LDV. We then differentiated the measured velocities to get the acceleration profiles. Finally, we compared the reconstructed acceleration signals with the actual acceleration signals recorded from physical buttons in Figure 3.10. We observed a good match between the actual and reconstructed acceleration signals in the time domain. Obviously, they did not match in the frequency domain since the frequency spectrum of the reconstructed acceleration signals were dominated by the resonance frequency of the HapTable.

3.6 Haptic Rendering of Digital Buttons based on Finger Contact Area

Force is an important factor in actuating a physical button [Colton and Hollerbach, 2007, Alexander et al., 2014]. Some buttons are actuated by lightly tapping on the keys (such as the *Toggle Button* in our case) while others need higher actuation force

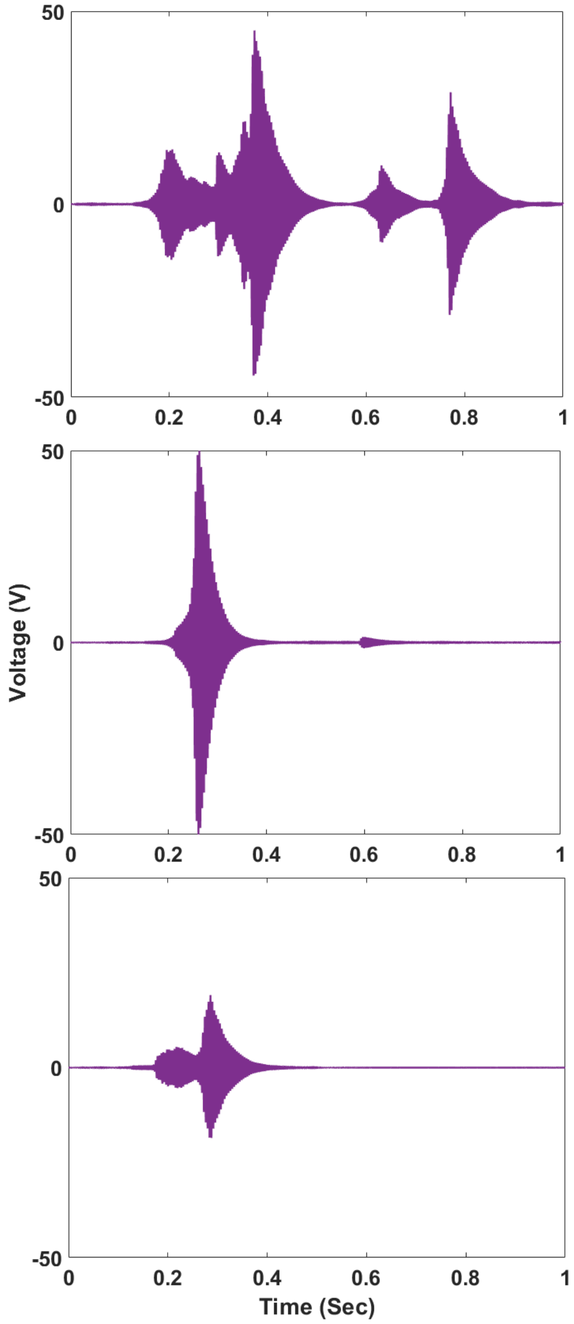


Figure 3.9: Voltage signals applied to the piezo patch A for digital *Latch Button* (top), *Toggle Button* (middle), and *Push Button* (bottom). The input voltage is 100Vpp.

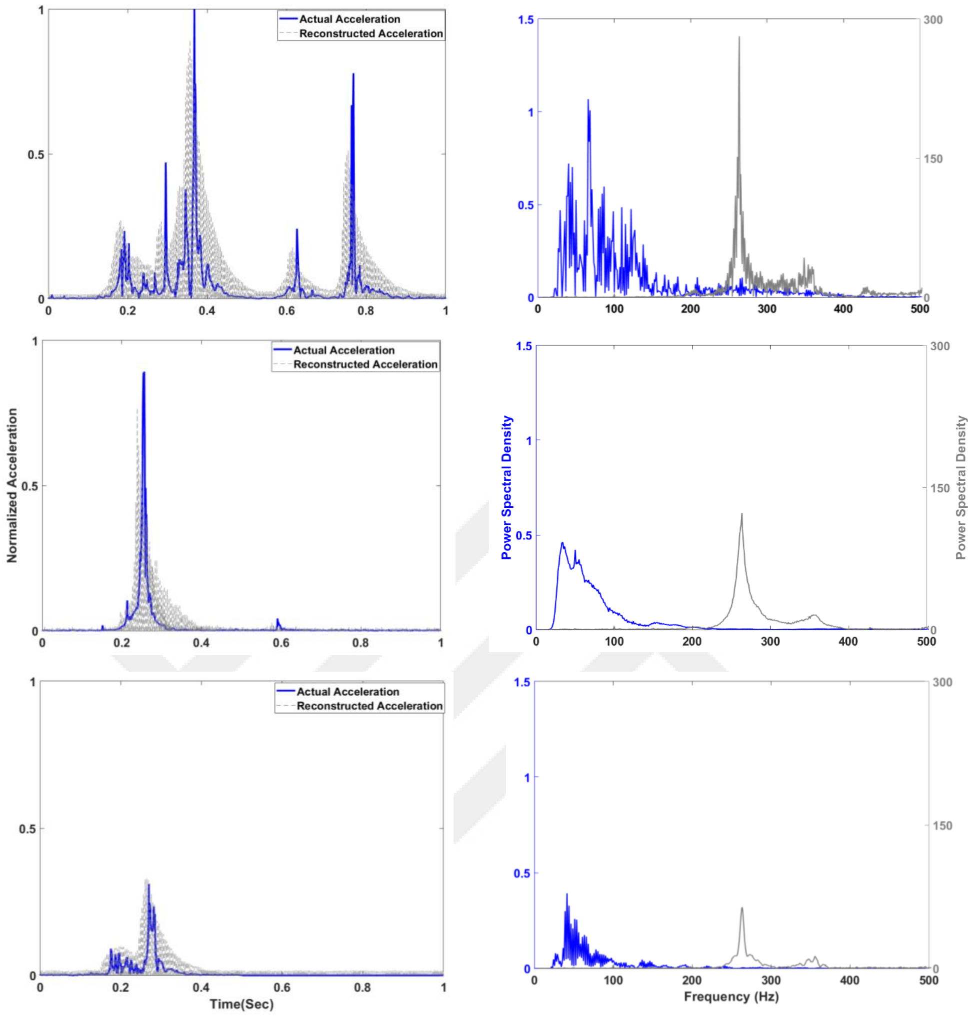


Figure 3.10: Comparison of the reconstructed acceleration signals (gray) with the recorded acceleration signals (blue) for *Latch Button* (top), *Toggle Button* (middle), and *Push Button* (bottom) along with the frequency spectrum of the recorded acceleration signals (blue) and reconstructed acceleration signals (gray) on the right column.

(such as the *Latch Button* in our case). Typically, touch surfaces are not equipped with force sensors. Therefore, we cannot directly use force information to actuate the digital buttons on mobile phones and tablets.

Existing literature shows that the apparent finger contact area grows proportionally with applied normal force [Johnson and Johnson, 1987, van Kuilenburg et al., 2015]. Therefore, we related the mean normal force required to activate physical buttons (see the upper right corner in Figure 3.8) with the finger contact area of the participants to activate digital buttons. Hence, *Latch Button* required the largest area of finger contact while *Toggle Button* required the smallest area of finger contact. For implementation purposes, we simply defined three conditions to activate each digital button as depicted in Figure 3.11, where A_{min} and A_{max} represent the contact areas corresponding to low and high finger pressure. The digital button is activated when the participant applies sufficient pressure to the touch surface with her/his finger such that the instantaneous contact area exceeds the pre-determined threshold values (Figure 3.11).

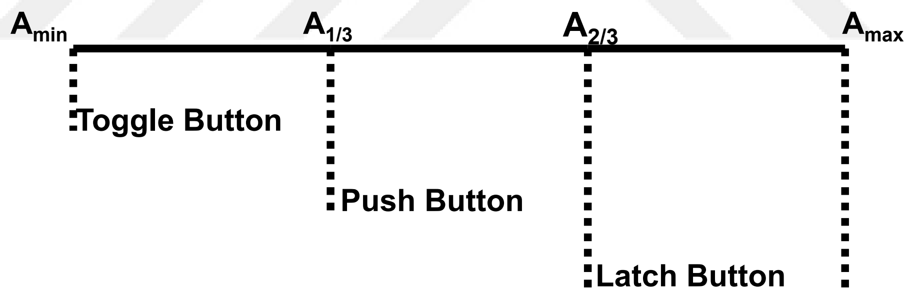


Figure 3.11: Minimum force required to activate each of the three digital buttons based on the finger contact area.

Obviously, the mapping between normal force and finger contact area is not linear when Hertz contact model is considered. However, our visualization table (HapTable) is not equipped with a force/pressure sensor. Therefore, it was not possible to activate the digital buttons based on the recorded force values of participants. Moreover, we did not measure the finger contact area of the participants simultaneously with the force applied to the physical buttons in our experimental setup (Figure 3.5) during our recording session (Section 2.2). Also, we did not control their finger orientation while they pressed the physical buttons, which affects the size of the contact area. For those reasons, in our study, we measured the finger contact area of each participant using an IR camera and then use a simple linear model, based on the recorded force data from physical buttons, to activate the digital buttons.

3.7 Experiment-I: Matching Experiment

In this experiment, we asked participants to match digital buttons with their physical counterparts by pressing the digital button on the interaction surface of HapTable and relate it with one of the three physical buttons.

3.7.1 Participants

Twenty participants (12 males and 8 females with an average age of 29.12 ± 6.42 years) participated in this experiment. Sixteen participants were right-handed and the rest were left-handed. All of them were graduate students and everyday users of mobile phones. The participants read and signed a consent form before the experiment. The form was approved by the Ethical Committee for Human Participants of Koç University.

3.7.2 Experimental Design and Procedure

A 2×2 latin square design was used to investigate if the participants' matching performance was improved after learning the corresponding stimulus for each physical button [Foehrenbach et al., 2009, Ma et al., 2015]. The participants were randomly assigned to one of these experimental groups. Each participant took part in two experimental sessions conducted on two alternate days. Each session involved four steps as shown in Figure 3.12 below:

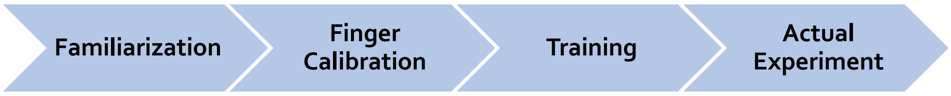


Figure 3.12: Four steps involved in the matching experiment.

Familiarization

Participants pressed each of the three physical buttons, ten times to familiarize themselves with the haptic feedback resulting from pressing these buttons. They were blindfolded to prevent any visual bias but instructed to pay attention to the tactile cues while they were interacting with physical buttons.

Finger Calibration

As reported in the earlier studies [van Kuilenburg, 2013, Delhaye et al., 2014], humans have different finger contact areas for the same normal force. To display personalized haptic feedback to each participant in our study, we measured the participants' finger contact area before the actual experiment while they were pressing on the touch surface, as if they were activating a digital button, under two different contact conditions: (a) low (A_{min}) and (b) high (A_{max}) finger pressure. Participants were asked to press the touch surface five times for each contact condition. The mean values for A_{min} and A_{max} were utilized in activating digital buttons based on the conditions set in Figure 3.11.

Training

This step was designed to familiarize participants with the experimental setup, and the haptic feedback displayed for the digital buttons on HapTable. During this step, participants were allowed to ask questions. Each participant completed nine trials (3 repetition x 3 digital buttons). In each trial, participants received haptic feedback according to their contact area and button type and asked to match it with one of the three physical buttons. We provided confirmation to Group-II about the correctness of their selected choices during the training step on Day-I, but not on Day-II. Group-I received confirmation about the correctness of their choice during this step on Day-II, but not on Day-I (Table 3.1).

Table 3.1: Latin square design used for Experiment-I.

	Day-I	**Day-II**
Group-I	No Confirmation	Confirmation
Group-II	Confirmation	No Confirmation

Actual Experiment

There were thirty trials in the actual experiment (10 repetitions x 3 digital buttons). Participants were not allowed to ask any questions. They wore noise-canceling headphones to eliminate audio cues. The task was to press the digital button on the HapTable to feel the vibrotactile signal and relate it with one of the three physical buttons they experienced earlier in the familiarization step.

3.8 Experiment-II: Subjective Rating Experiment

Experiment-II aimed to investigate how effectively we were able to render the haptic feeling of physical buttons in the digital domain. The experiment consisted of two steps. In the first step, we collected adjectives from the participants through a survey, describing their tactile sensations of the three physical buttons. In the second step, participants experimented with the physical and digital buttons and rated their subjective experiences via those adjectives.

3.8.1 Collecting Adjectives

The participants were asked to write down the adjectives that could be associated with the tactile sensation of all three physical buttons. We sorted the most frequently appeared adjectives in their list and selected the top nine adjective pairs with opposite meanings (Table 3.2). We removed the stiff/springy adjective pair because our current setup cannot render the stiffness/springiness of a button.

Table 3.2: List of nine adjective pairs used for adjective ratings in Experiment-II.

Pair No.	Adjectives		
1	Unpleasant	$\Longleftrightarrow$	Pleasant
2	Uncomfortable	$\Longleftrightarrow$	Comfortable
3	Unclear	$\Longleftrightarrow$	Clear
4	Unstable	$\Longleftrightarrow$	Stable
5	Delayed	$\Longleftrightarrow$	Quick
6	Unreliable	$\Longleftrightarrow$	Reliable
7	Rough	$\Longleftrightarrow$	Smooth
8*	Hard	$\Longleftrightarrow$	Soft
9*	Stiff	$\Longleftrightarrow$	Springy

*Adjective pair was removed after the pilot study.

After a pilot study conducted with ten new participants, we also removed the hard/soft adjective pair as the participants reported difficulty in attributing hardness/softness to the digital buttons. Hence, we ended up with seven adjective pairs.

3.8.2 Subjective Evaluation

In this step, the same twenty participants from experiment-I rated their tactile sensations of physical and digital buttons using the seven adjective pairs shown in Table 3.2. We designed a simple GUI to collect adjective ratings for each of the three physical and digital buttons (Figure 3.13). Participants were allowed to

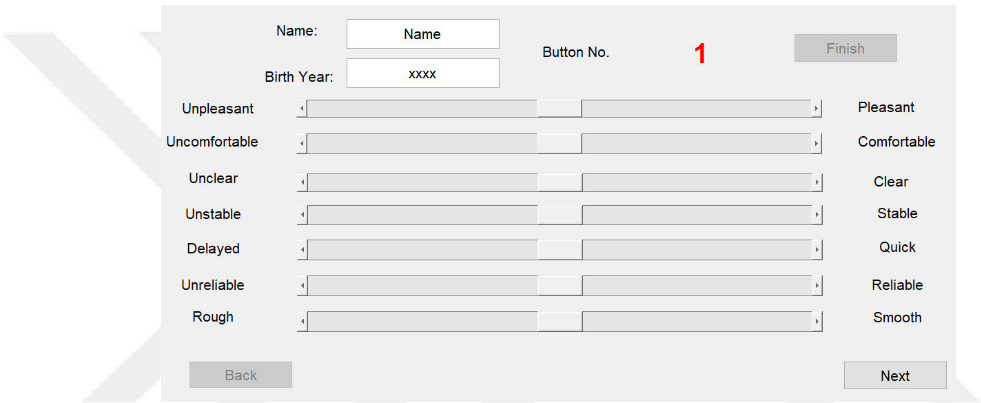


Figure 3.13: The user interface for the adjective ratings.

experiment with each button as many times as they wanted. Then, they were asked to manipulate the slider bar of each adjective pair to rate their subjective feelings. All slider bars were centered at the beginning of evaluation for each button. On average, the experiment took thirty minutes for each participant.

3.9 Results

3.9.1 Experiment-I

Figure 3.14 shows the confusion matrices for the responses of both groups on alternate days. The diagonal entries in these matrices show the correct recognition rate in percentage for each button, known as true positive (TP) values whereas the off-diagonal entries are classified as errors. The total number of false negatives (FN) for a button is the sum of the values in the corresponding rows, excluding (TP). The total number of false positives (FP) for a button is the sum of the values of the corresponding columns excluding (TP). The total number of true negatives (TN) for a button is the sum of all columns and rows excluding the column and row of that button.

The following performance metrics were used to analyze the results [Landis and Koch, 1977, Fawcett, 2006, Sokolova and Lapalme, 2009]:

(a) Accuracy (ACC) is calculated as sum of the correct classifications divided by the total number of classifications (Equation 3.2).

$$ACC = \frac{TP + TN}{Total} \tag{3.2}$$

(b) Precision (PREC) is calculated as the number of correct classifications divided by the total number of positive predictions for a specific button (Equation 3.3).

$$PREC = \frac{TP}{TP + FP} \tag{3.3}$$

(c) Sensitivity (SN), also called recall, is calculated as the number of correct positive predictions divided by the total number of stimuli presented for a specific button (Equation 3.4).

$$SN = \frac{TP}{TP + FN} \tag{3.4}$$

The sensitivity per button varied from 68% (*Push Button*) to 75% (*Latch Button*) for Group-I on Day-I, (no confirmation provided during training on digital buttons, see Figure 3.14a). After providing confirmation to Group-I during their training on Day-II for digital buttons, the sensitivity was improved by 11% for *Push Button*, 16% for *Toggle Button*, and 17% for *Latch Button* (see Figure 3.14b). The performance

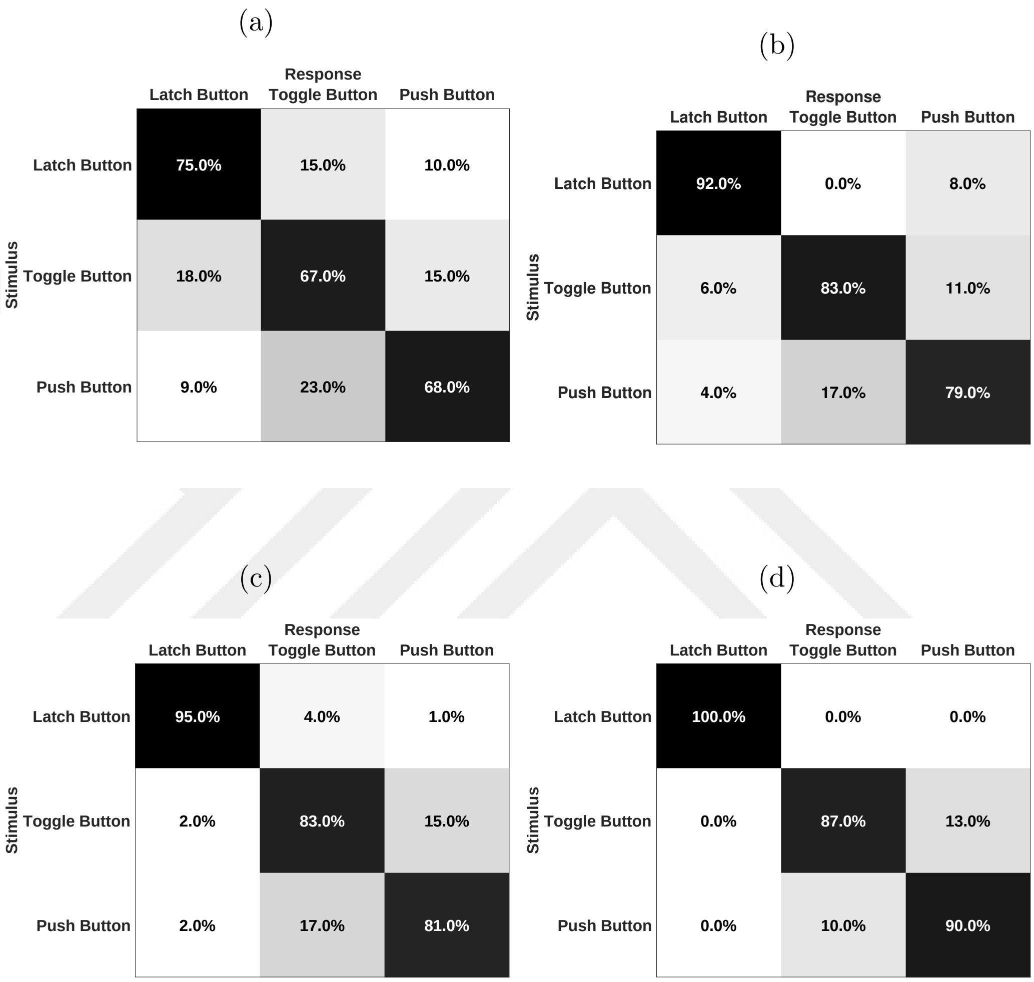


Figure 3.14: Confusion matrices for the responses of participants in (a) Group-I with no confirmation (Day-I), (b) Group-I with confirmation (Day-II), (c) Group-II with confirmation (Day-I), and (d) Group-II with no confirmation (Day-II).

metrics in Table 3.3 confirm that the accuracy of identifying *Toggle Button* was improved by 12.34% followed by *Latch Button* (11.33%) and *Push Button* (5.67%) for Group-I on Day-II, when confirmation was provided during training on digital buttons.

Table 3.3: Comparison of performance metrics of Group-I for Day-I and Day-II

Metrics	**Group-I (Day-I)**			**Group-I (Day-II)**		
	Latch Button	*Toggle Button*	*Push Button*	*Latch Button*	*Toggle Button*	*Push Button*
ACC (%)	82.67%	76.33%	81.00%	94.00%	88.67%	86.67%
PREC (%)	73.53%	63.81%	73.12%	90.20%	83.0%	80.61%
SN (%)	75%	67%	68%	92%	83%	79%

The sensitivity scores of participants in Group-II varied from 81% (*Push Button*) to 95% (*Latch Button*) on Day-I (confirmation provided during training, see Figure 3.14c). Sensitivity was improved by 9% for *Push Button*, 4% for *Toggle Button*, and 5% for *Latch Button* on Day-II when Group-II was not provided with any confirmation during their training on digital buttons (see Figure 3.14d). It is further confirmed from the performance metrics in Table 3.4 that Group-II could identify *Latch Button* with 100% precision followed by *Toggle Button* (89.69%) and *Push Button* (87.38%) on Day-II when no confirmation was provided during training on digital buttons.

Figure 3.14 shows that if confirmation was provided to the participants during training on the digital buttons, their performance was improved especially in the

Table 3.4: Comparison of performance metrics of Group-II for Day-I and Day-II

Metrics	**Group-II (Day-I)**			**Group-II (Day-II)**		
	Latch Button	*Toggle Button*	*Push Button*	*Latch Button*	*Toggle Button*	*Push Button*
ACC (%)	97.00%	87.33%	88.33%	100%	92.33%	92.33%
PREC (%)	95.96%	79.81%	83.51%	100%	89.69%	87.38%
SN (%)	95%	83%	81%	100%	87%	90%

case of *Toggle Button* and *Push Button*. However, we observed that both groups found *Latch Button* distinct as compared to *Toggle Button* and *Push Button*, but confused *Toggle Button* with *Push Button* irrespective of the confirmation provided.

We further performed a three-way ANOVA on the performance metrics with two within-subjects factors (confirmation and button-type; latch, toggle, and push button) and one between-subjects factor (group number). First, we performed the Mauchly's test of sphericity to check whether the differences between the levels of the within-subject factors have equal variance. If the sphericity assumption was violated, the degrees of freedom were corrected using Greenhouse-Geisser correction. Then, Bonferroni corrected post-hoc analysis was carried out to investigate where the statistically significant differences between the levels of within-subject factors lie.

Providing confirmation to the participants during training has a significant main effect on all the performance metrics ($p < 0.01$). When the confirmation was provided, the performance metrics were improved. The button-type also has a statistically significant main effect on all of the performance metrics ($p < 0.01$). Compared to *Toggle* and *Push Button*, *Latch Button* had the highest accuracy, precision, and sensitivity scores.

There was a significant interaction between confirmation and group number ($p < 0.01$), suggesting that, providing confirmation to Group-II first and Group-I later during training session yields a different effect on the performance metrics. On Day-I, Group-II performed better than Group-I, since they received confirmation. The interaction between the button-type and group number was not significant. The interaction effect between confirmation and button-type was also non-significant.

Our post-hoc analysis showed that participants were significantly better at relating digital *Latch Button* with its physical counterpart in comparison with *Toggle Button* and *Push Button* ($p < 0.001$). However, we could not find significant differences in relating *Toggle Button* and *Push Button* to their physical counterparts irrespective of the confirmation provided during the training session.

3.9.2 Experiment-II

We applied a normalization to the subjective ratings based on the method suggested by [Murray et al., 2003]. For this purpose, we first computed the geometric mean of all responses, called Grand Geometric Mean (GGM), and the geometric mean of each participant (GM_P). We then obtained the normalized value for each participant by GGM/GM_P.

The average ratings obtained in Experiment-II and their standard deviations are shown in Figure 3.15 for each button. Participants have rated digital *Latch Button* similar to physical *Latch Button* on *Unstable-Stable*, *Unclear-Clear* and *Unreliable-Reliable* adjective pairs. However, they felt digital *Latch Button* more pleasant, comfortable, quick, and smooth compared to its physical counterpart. Participants have felt digital *Toggle Button* similar to its physical counterpart for almost all adjective pairs except for *Unreliable-Reliable*. According to participants' ratings, digital *Toggle Button* is less reliable than its physical counterpart. They felt digital

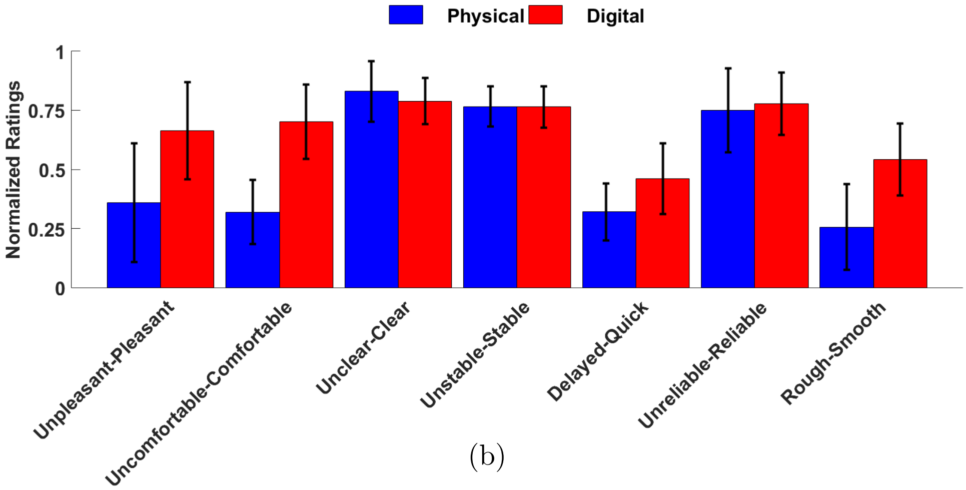
Push Button similar to its physical counterpart for *Rough-Smooth* adjective pair. We conducted a two-way multivariate analysis of variance (MANOVA) as described by [Meyers et al., 2016] with two independent variables (button-type, button-category; physical and digital) and seven dependent variables (seven adjective pairs listed in Table 3.2).

The MANOVA found significant main effects of both button-category ($F(7, 108) = 7.46, p < 0.001, \eta^2 = 0.326$), and button-type ($F(14, 218) = 26.41, p < 0.001, \eta^2 = 0.63$) on the combined dependent variables. The interaction between button-category and button-type was also significant ($F(14, 218) = 5.36, p < 0.001, \eta^2 = 0.26$). Individual ANOVA found a non-significant main effect of button-category for two adjective pairs: *Unclear-Clear* and *Unreliable-Reliable*, showing that participants have rated digital buttons similar to their physical counterparts for these adjective pairs. Our post-hoc analysis showed that participants rated two of the three digital buttons (*Toggle Button* and *Push Button*) similar to their physical counterparts for four adjective pairs: *Unpleasant-Pleasant, Uncomfortable-Comfortable, Delayed-Quick,* and *Rough-Smooth.* Digital *Latch Button* was rated similar to its physical counterpart for three adjective pairs: *Unclear-Clear, Unstable-Stable,* and *Unreliable-Reliable.*

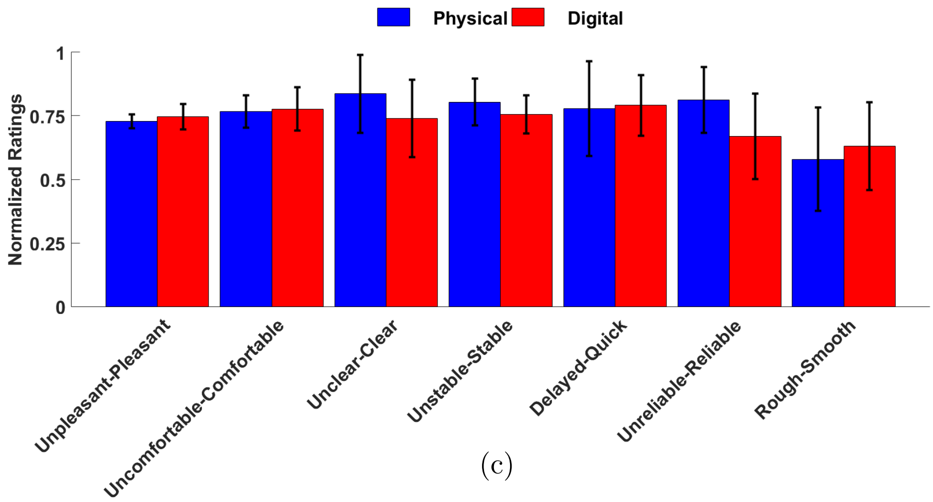
3.10 Discussion

In this study, we recorded force, acceleration, and voltage data for activation state from three physical buttons to identify their distinct response characteristics. We used the acceleration profile recorded for each physical button to generate the vibrotactile stimulus for its digital counterpart. In this regard, we first obtained the representative acceleration signal of each participant and button by applying a DTW algorithm to recorded acceleration profiles, and then we applied DTW one more time to obtain the representative signals for each button among all participants. After obtaining the representative signals for each button, we mapped the acceleration profile to the actuation voltage signal using the transfer function of the interaction

(a)



(b)



(c)

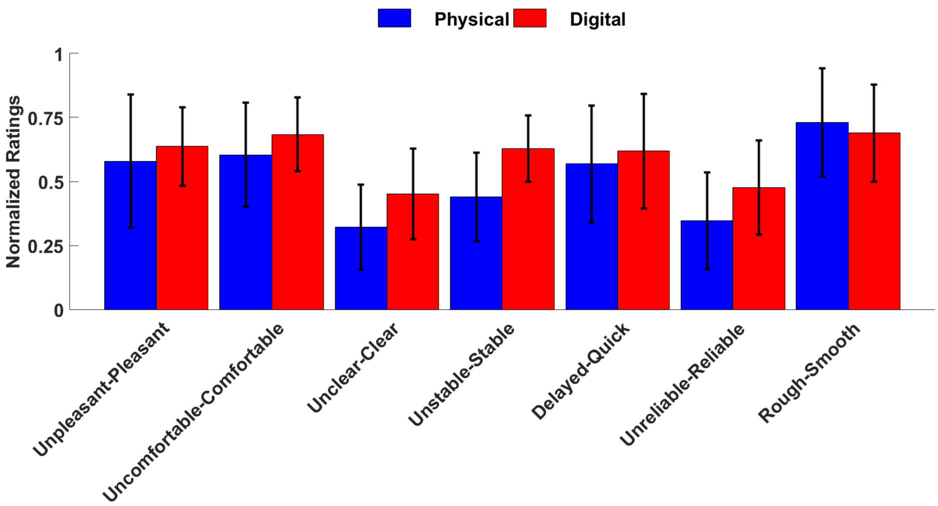


Figure 3.15: Normalized adjective ratings of all three physical and digital buttons with their standard deviations: (a) *Latch Button*, (b) *Toggle Button*, and (c) *Push Button*.

surface for the point where the digital buttons were displayed to the users. Since it was not possible to display force feedback to the users in our system, the information gained from the recorded force data was associated with the finger contact area of each participant pressing the digital button to determine the instant of its activation.

We conducted a user study in which we asked the participants to match the vibrotactile stimulus, displayed to them through the touch surface, with one of the three physical buttons that they had interacted with. Hence, the chance level of the experiment was 33%. The correct recognition rate of both groups was significantly higher than the chance level for each button (Tables 3.3 and 3.4).

Our experimental results revealed that both groups had confusion in matching *Toggle Button* and *Push Button* to their physical counterparts irrespective of the availability of the confirmation during training step. Six out of ten participants in Group-I on Day-I perfectly matched the digital *Latch Button* to its physical counterpart, whereas three participants confused *Toggle Button* with *Push Button* and vice versa. Only, one participant perfectly matched all digital buttons to their physical counterparts for all trials. Note that there was no confirmation provided to Group-I on Day-I. After providing confirmation during training, the overall performance was improved by 15%. However, the *Toggle Button* was still confused with *Push Button*. Eight participants from Group-II on Day-I could match digital *Latch Button* to its physical counterpart with 100% accuracy. Two out of eight participants perfectly matched digital buttons with their physical counterparts and three participants achieved 99% accuracy and confused *Toggle Button* with *Push Button* only once. Rest of the participants confused *Latch Button* with *Toggle Button* and *Toggle Button* with *Push Button*. The overall accuracy was 86.33% for Group-II on Day-I and improved by 6% on Day-II when no confirmation was provided during training. Overall, the participants correctly matched the given digital buttons with their physical counterparts with an accuracy of 83%.

After the matching experiment, we verbally asked participants to comment on their subjective experience with digital buttons. Majority of the participants were confident that they matched the *Latch Button* correctly. Some participants stated that the duration of haptic stimuli (vibration duration) helped them to distinguish the *Toggle Button* from *Push Button*, whereas some stated that they made a decision based on the pressure they applied to the touchscreen to activate the button, which is related to the finger contact area. Fifteen out of twenty participants preferred *Toggle Button* and *Push Button* over *Latch Button*. These results are in line with some previous studies by [Koskinen et al., 2008, Lylykangas et al., 2011] and [Park et al., 2011]. They emphasized the importance of keeping duration short for button click vibrations. Furthermore, [Shin et al., 2014] also highlighted that tactile stimulus responding to pressing a digital button on touch surface with a rapid response time provides a realistic feeling of physically clicking a button. This is also confirmed in our experimental results. Participants have preferred digital buttons with short vibration duration (*Toggle Button* and *Push Button*) as compared to the one with longer vibration duration (*Latch Button* in our case).

We also asked participants to rate their subjective tactile feelings of physical and digital buttons using seven adjective pairs (Table 3.2). Our statistical analysis revealed that participants have rated two out of three digital buttons (*Toggle Button* and *Push Button*) similar to their physical counterparts for four adjective pairs: *Unpleasant-Pleasant, Uncomfortable-Comfortable, Delayed-Quick,* and *Rough-Smooth.* Furthermore, our results also showed that participants perceived digital buttons more pleasant, comfortable, and smooth as compared to their physical counterparts.

Chapter 4

EXPLORATION STRATEGIES FOR TACTILE GRAPHICS DISPLAYED BY ELECTROVIBRATION ON A TOUCHSCREEN

Summary

In this chapter, we report the results of our experiments performed with human participants to investigate the recognition rate and time of five tactile shapes (i.e., triangle, square, pentagon, hexagon, and octagon) rendered by electrovibration on a touchscreen using three different methods and displayed in prototypical orientations and non-prototypical orientations (i.e., 15 degrees CW and CCW to the prototypical orientation). The results showed that the recognition rate was higher when the haptically active area was larger. However, as the number of edges was increased, the recognition time increased and the recognition rate dropped significantly, arriving to a value slightly higher than the chance rate of 20% for non-prototypical octagon. Moreover, the recognition time for inside rendering condition was significantly shorter as compared to edge and outside rendering conditions and edge rendering condition led to the longest recognition time. We also recorded the participants' finger movements on the touchscreen to examine their haptic exploration strategies. Based on our temporal analysis, we classified six exploration strategies adopted by participants to identify the shapes, which were different for the prototypical and non-prototypical shapes. Moreover, our spatial analysis revealed that the participants first used global scanning to extract the coarse features of the displayed shapes, and then they applied local scanning to identify finer details, but needed another global scan for final confirmation in the case of non-prototypical shapes,

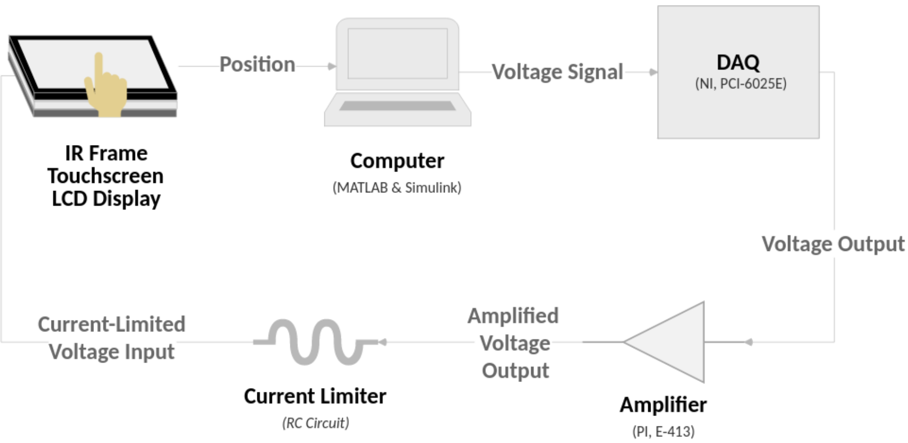
possibly due to the current limitations of electrovibration technology in displaying tactile stimuli to a user. We observed that it was highly difficult to follow the edges of shapes and recognize shapes with more than five edges under electrovibration when a single finger was used for exploration.

4.1 Experimental Setup

A surface capacitive touchscreen (SCT3250, 3M Inc.) was used to display tactile stimuli to participants. The desired voltage signal was generated by a DAQ card (PCI-6025E, National Instruments Inc.) and boosted by an amplifier (E-413, PI Inc.) before transmitted to the touchscreen through a current limiter. Figure 4.1a depicts the process of generating voltage signal for rendering tactile shapes on the touchscreen. The waveform, amplitude, and the frequency of the voltage signal were a square wave, 200 Vpp, and 120 Hz, respectively, where the wave characteristics were selected to provide the most differentiable haptic sensation possible ([Vardar et al., 2017a]). An LCD was positioned below the touchscreen for visual feedback to participants and to let them pick the perceived tactile shape using a mouse and a GUI. An IR frame (NIB170BP, Nexio Inc.) was placed above the touchscreen to detect and record the position of participants' index finger. MATLAB and Simulink Desktop Real-Time were utilized to develop the GUI to record the participants' responses and to display electrovibration to participants in real-time based on their finger positions, respectively. Figure 4.1b illustrates the setup used for our experiments.

4.2 Experiment-I

We investigated the effect of number of edges and rendering conditions on the recognition rate and time of 2D equilateral tactile shapes. Also, we examined the strategies followed by the participants while exploring these shapes on the touchscreen.



(a)

(b)

Figure 4.1: (a) Schematic showing how voltage signal is generated, processed, and transmitted to the touchscreen. (b) Illustration of the experimental setup used in our study.

4.2.1 Participants

Nine participants (5 male, 4 female with an average age of 27 $\pm$ 6.7 years) participated in this experiment. All of them were graduate students and everyday users of mobile devices. The participants read and signed a consent form before the experiment. The Ethical Committee of Koç University approved the form for human participants.

4.2.2 Stimuli

The experimental stimuli consisted of five geometrical shapes (triangle, square, pentagon, hexagon, and octagon) displayed under three rendering conditions; electrovibration was displayed 1) inside the shape (*Inside*), 2) on the edges of the shape (*Edge*), and outside the shape (*Outside*) as shown in Figure 4.2. In edge rendering condition, the width of edges was set to 10 mm, which was chosen based on the guidelines provided by [Palani et al., 2018] for vibrotactile rendering of virtual lines. The size of shapes was selected to fit in a circle with a diameter of 10 cm (see the dotted gray-colored inner circle in Figure 4.2a). This diameter was selected by trial and error such that the shapes were sufficiently large and could be detected by finger with ease. Although the shapes were not displayed visually to the participants during the actual experiment, a circle with a diameter of 15 cm (see the dashed red-colored outer circle in Figure 4.2a) was visually displayed to the participants to help them locate the rendered tactile shape more easily on the touchscreen.

4.2.3 Procedure

Before the actual experiment, participants performed a training session to familiarize themselves with the experimental setup, the tactile feedback displayed for the shapes, and rendering conditions. Each shape was displayed once to the participants in sequential order under the three rendering conditions (*Inside*, *Edge*, *Outside*). Participants were allowed to ask questions during the training session.

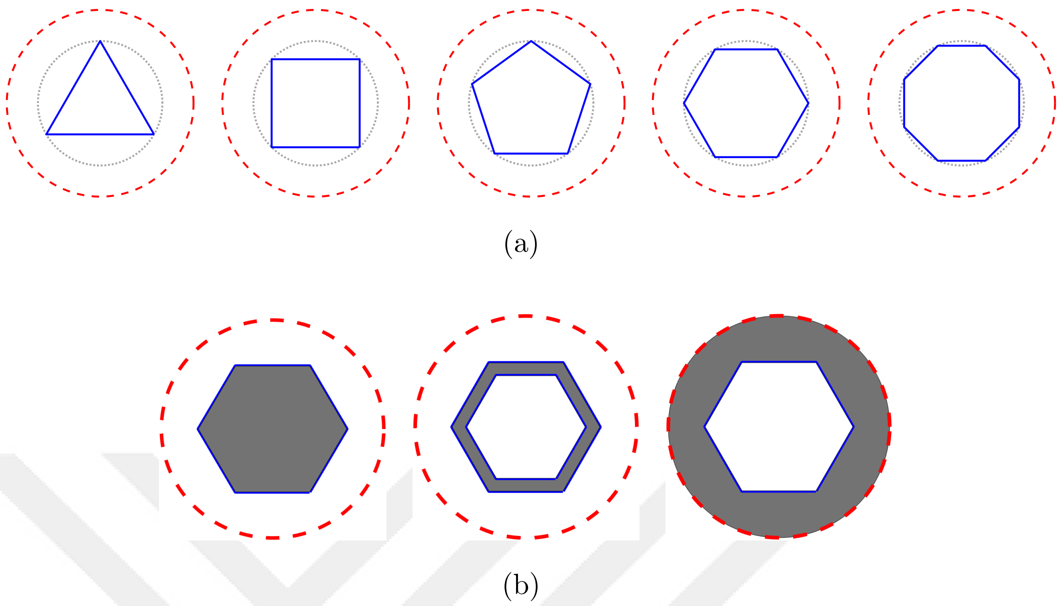


Figure 4.2: (a) Five tactile shapes were displayed to the participants via electrovibration under three rendering conditions (b) (left to right); electrovibration was displayed inside the shape (*Inside*), on the edges (*Edge*), and outside of the shape (*Outside*). The shaded areas in (b) illustrate the haptically active areas in all rendering conditions. Solid blue-colored lines in (a) represent rendered shapes, dotted gray-colored circle represents circumcircle of the shapes, and dashed red-colored circle represents the area where tactile shapes were displayed to the participants. Only red dashed circle was displayed to the participants visually during the actual experiment.

After the training session, participants performed the actual experiment. The task was to explore the tactile shapes on the touchscreen using the index finger and then select the perceived shape from the five choices (Triangle, Square, Pentagon, Hexagon, Octagon) presented on the GUI using a mouse. There was no time limit in the experiment. Participants were not allowed to ask any questions during the actual experiment. They were asked to put on noise-canceling headphones to prevent any external noise affecting their haptic perception.

The experiment was performed in two separate sessions with one-day interval between them. There were 30 trials in each session (5 shapes × 3 rendering conditions × 2 repetitions). Hence, the total number of trials for each participant was 60. The trials were randomized while the same randomization pattern was used for all participants.

4.2.4 Analysis

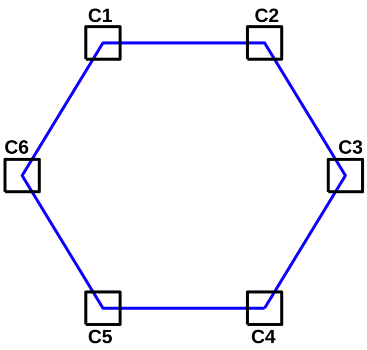
The study was a within-subjects design with two independent variables; rendering conditions and number of edges. We analyzed the user performance based on the following metrics:

- Recognition rate: The ratio of the correctly identified shape to the total number of displayed shapes.
- Recognition time: The time taken by the participants to correctly identify the displayed shape.

Furthermore, we recorded the participants' finger position as a function of time to investigate the strategies followed by the participants during the exploration process based on the spatial and temporal information. The collected data allowed us to generate animated video files for all the interactions made by each participant during the exploration of shapes. These video files were then used to characterize and code the exploration strategies followed by the participants.

In spatial analysis, we searched for any salient spatial features that help participants to distinguish one shape from another. We used the following metrics for spatial analysis:

- **Number of touches to each corner** was counted by defining a small square region of 1.5 cm in size around each corner as shown in Figure 4.3a. The corners



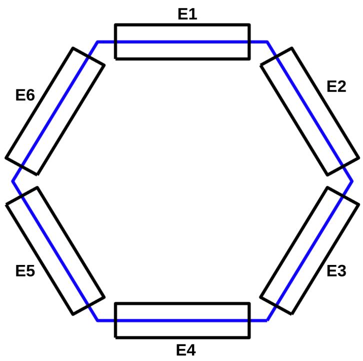


Figure 4.3: All the touches made inside the square box at each corner (a) and the rectangular box at each edge (b) were counted.

were labeled by starting from the top-left corner and moving in clockwise direction as shown in Figure 4.3a.

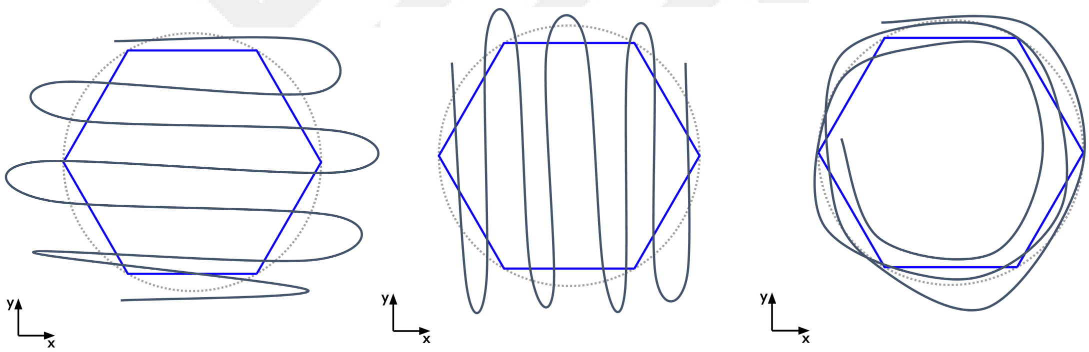
- **Number of touches to each edge** was counted by defining a rectangular region of 3.5 cm × 1.5 cm in size along each edge as shown in Figure 4.3b. The edges were labeled by starting from the top edge and moving in clockwise direction (Figure 4.3b).

- **Number of touches to the haptically active area:** All the touches occurred in the rendered area were counted. For example, if the rendering method was "*Inside*", the haptically active area was inside the shape. Hence, all the touches inside the shape were counted.

In temporal analysis, we investigated participants' exploration strategies and identified two main strategies; global scanning and local scanning, as described below:

- **Global scanning:** If a path was traced using long and continuous movements for the identification of global features of the rendered shape (see Figure 4.4), the exploration was classified as global scanning. Global scanning was further categorized into three sub-categories based on the exploratory movements (Figure 4.4):

- **Global-horizontal:** If the scanning movements were along the x-axis, the exploration was classified as global-horizontal (Figure 4.4a).
- **Global-vertical:** If the scanning movements were along the y-axis, the exploration was classified as global-vertical (Figure 4.4b).
- **Global-others:** All other movement patterns such as circling and diagonal were classified as global-others (Figure 4.4c).



(a) (b) (c)

Figure 4.4: The strategies followed by the participants during global scanning: (a) global-horizontal, (b) global-vertical, and (c) global-others.

- **Local scanning:** If a path was traced using short and continuous movements for the identification of local features of the rendered shape (see Figure 4.5), the exploration was classified as local scanning. Local scanning was further categorized into three sub-categories based on the exploratory movements (Figure 4.5):

- **Local-edge-finding:** If the finger scanned an edge by moving back and forth along the edge, the exploration was classified as local-edge-finding (Figure 4.5a).
- **Local-edge-following:** If the finger made zig-zag movements along an edge, the exploration was classified as local-edge-following (Figure 4.5b).
- **Local-corner-finding:** If the finger circled around a corner, the exploration was classified as local-corner-finding (Figure 4.5c).

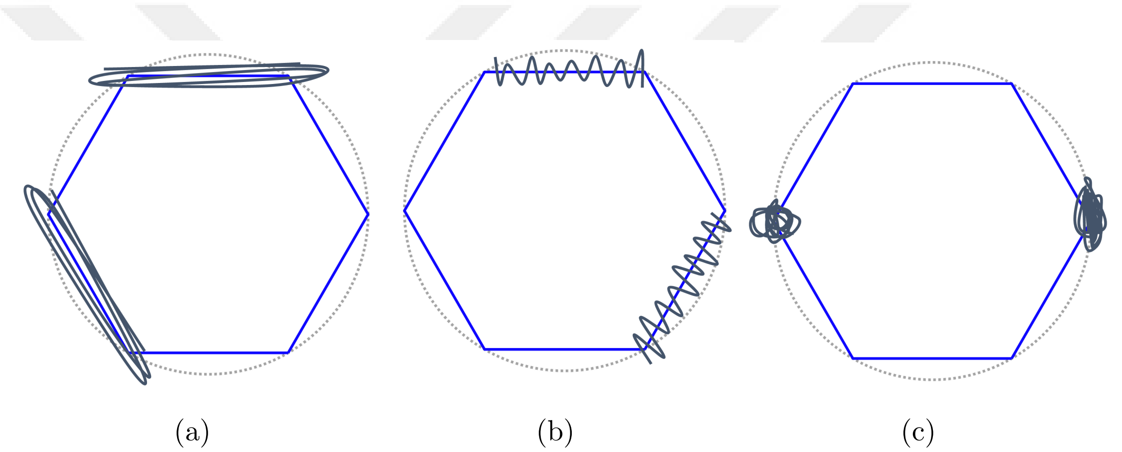


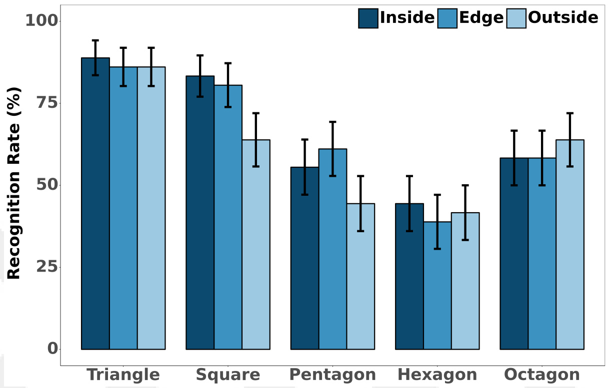
Figure 4.5: The strategies followed by the participants during local scanning: (a) local-edge-finding, (b)local-edge-following, and (c) local-corner-finding.

The time spent by the participants for each exploratory movement during local and global scanning was recorded.

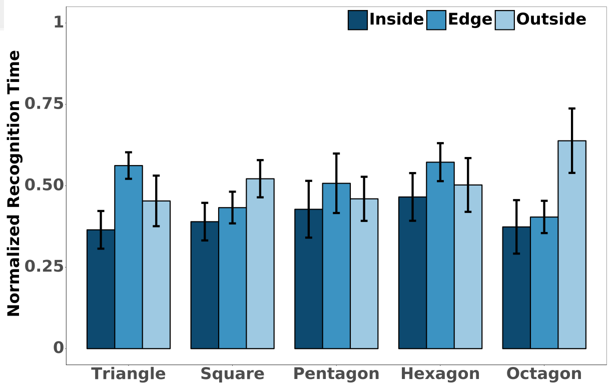
4.2.5 Results

Analysis of Recognition Rate and Time

Figure 4.6 shows the average recognition rate and time of all participants under the three rendering conditions. The results showed that irrespective of the rendering condition, as the number of edges was increased, the participants' correct recognition rate decreased except for octagon. The recognition rate for octagon was higher than that of hexagon under all three rendering conditions (Figure 4.6a). Also, the participants spent less time in recognizing the shapes in the case of *Inside* rendering condition as compared to the *Edge* and *Outside* rendering conditions.



(a)



(b)

Figure 4.6: Recognition rate (a) and normalized recognition time (b) for all shapes and rendering conditions.

We conducted a two-way with-in subjects multivariate analysis of variance (MANOVA) with two independent variables (rendering condition: *Inside*, *Edge*, *Outside*; number of edges: triangle (3), square (4), pentagon (5), hexagon (6), octagon (8)) and two dependent variables (recognition rate and recognition time). The MANOVA found significant main effects of rendering condition ($F(4, 32) = 3.225, p < 0.01, \eta^2 = 0.289$) and number of edges ($F(8, 64) = 3.701, p < 0.001, \eta^2 = 0.316$). The interaction effect between rendering condition and number of edges was non-significant ($F(16, 128) = 1.534, p > 0.05, \eta^2 = 0.161$). Individual ANOVA found a significant main effect of rendering condition on recognition time ($F(2, 16) = 7.529, p < 0.01, \eta^2 = 0.485$). Also, the effect of number of edges on recognition rate was significant ($F(4, 32) = 8.848, p < 0.001, \eta^2 = 0.525$). Our post-hoc analysis showed that *Inside* rendering condition resulted in significantly shorter recognition time as compared to the *Edge* and *Outside* rendering conditions ($p < 0.05$). *Edge* rendering condition led to the longest recognition time.

We constructed confusion matrices to further investigate the recognition rate of the participants under each rendering condition (Figure 4.7). The confusion matrices showed that hexagon was mostly confused with octagon in all three rendering conditions; when octagon was displayed to the participants, the confusion between hexagon and octagon was relatively low (11% for *Inside*, 22% for *Edge*, and 17% for *Outside* rendering conditions). However, when hexagon was displayed as the stimuli, the confusion was increased by 22% for *Inside*, 20% for *Edge* and 28% for *Outside* rendering conditions. These results suggest that the participants identified octagon more easily than hexagon.

Spatial Analysis

We investigated the number of touches to the edges and corners of all shapes under all three rendering conditions. Two-way MANOVA shows a significant multivariate effect for rendering conditions ($F(2, 106) = 23.752, p < 0.001, \eta^2 = 0.31$) and number of edges ($F(4, 106) = 48.320, p < 0.001, \eta^2 = 0.646$). Multivariate group analysis revealed that *Edge* rendering condition was significantly different from the *Inside* and *Outside* rendering conditions for all shapes except octagon. Our post-hoc analysis showed that the participants focused more on the corners in *Edge* rendering

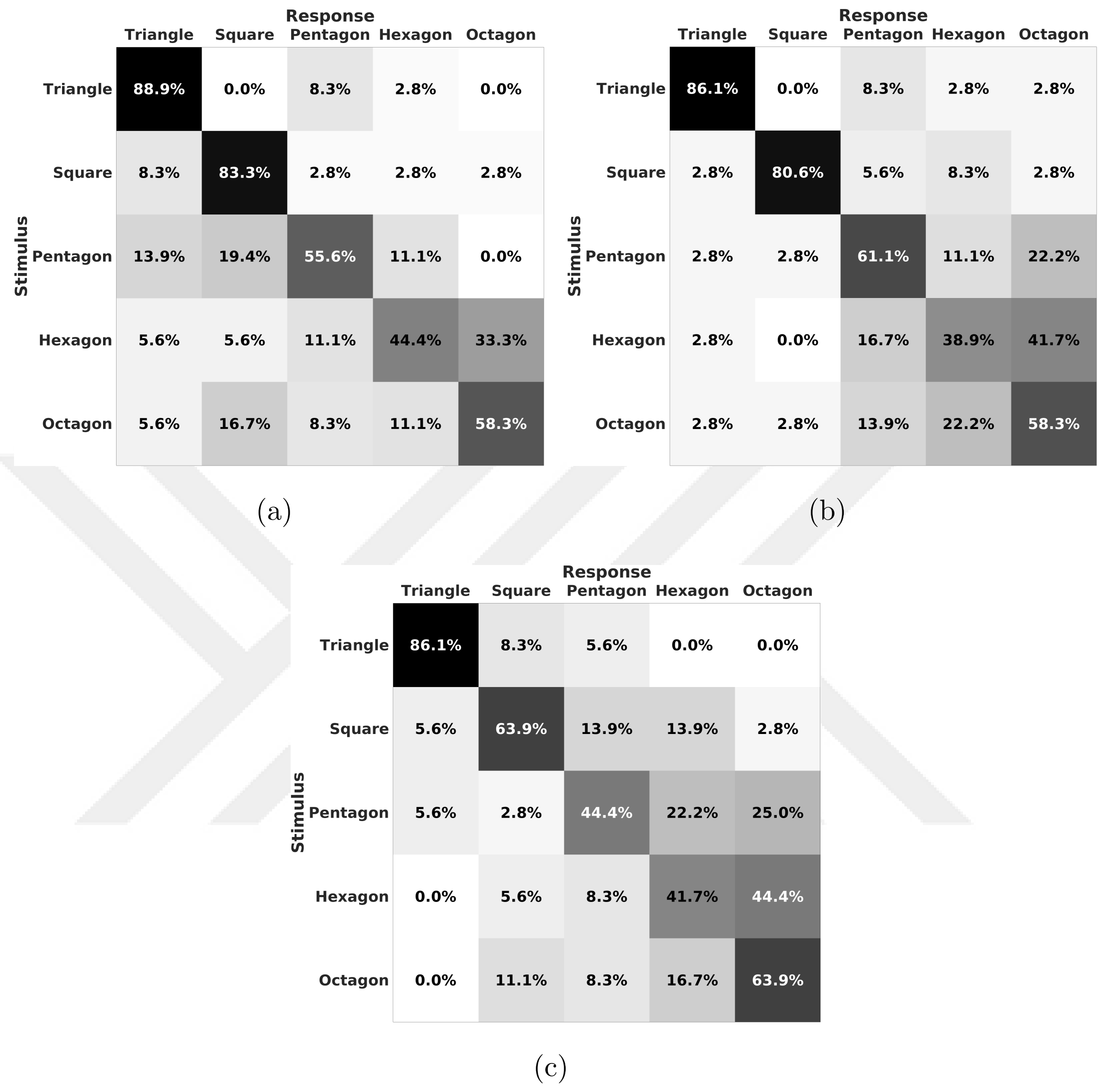


Figure 4.7: Confusion metrics of the recognition rate for (a) inside, (b) edge, and (c) outside rendering conditions.

condition, as observed from the frequency maps in Figure 4.8b and on the edges in *Inside* and *Outside* rendering conditions, as observed from Figures 4.8a and 4.8c.

We also found that the number of active touches (i.e., the number of touches in the regions where the electrovibration was turned on) was significantly lower under the *Edge* rendering condition compared to the other two rendering conditions.

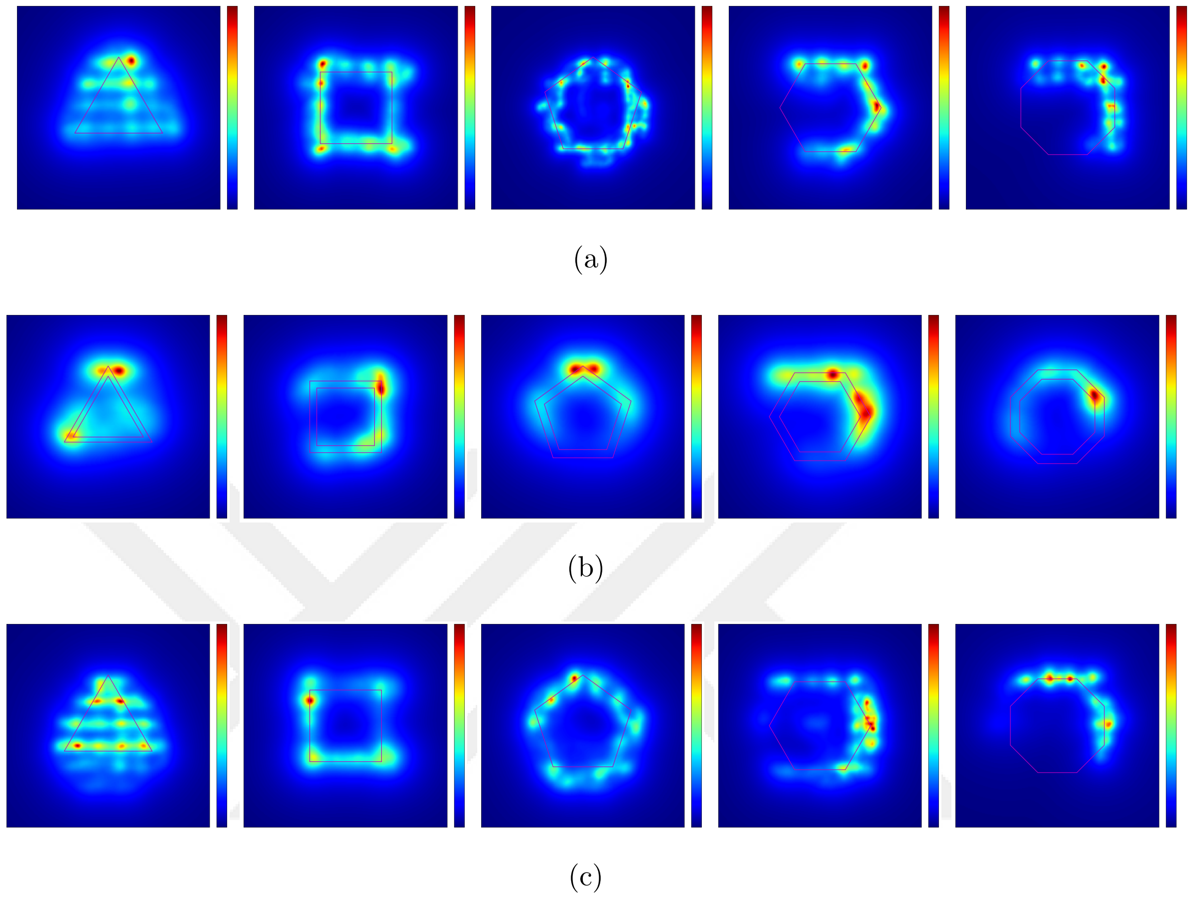


Figure 4.8: Frequency maps of randomly selected trials of participants (left to right: triangle, square, pentagon, hexagon, octagon) under three rendering conditions; (a) *Inside*, (b) *Edge*, and (c) *Outside*.

Since there were more white spaces with no stimulus (i.e., inactive region) in *Edge* rendering condition, the participants spent more time identifying the shapes. These outcomes align with the results reported by [Gorlewicz et al., 2020] for tactile shapes displayed by mechanical vibration.

Temporal Analysis

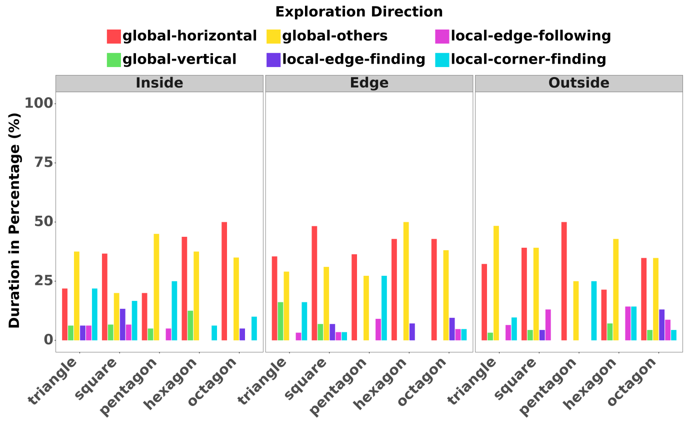
We investigated the exploration strategies used by the participants to examine the virtual shapes displayed on the touch surface. We reported the result of our analysis in terms of the starting, ending, most explored, and least explored strategies.

- The most common starting strategy adopted by the participants was global scanning with exploratory movement as horizontal (35%) for all shapes and rendering conditions (see the red colored bars in Figure 4.9a).

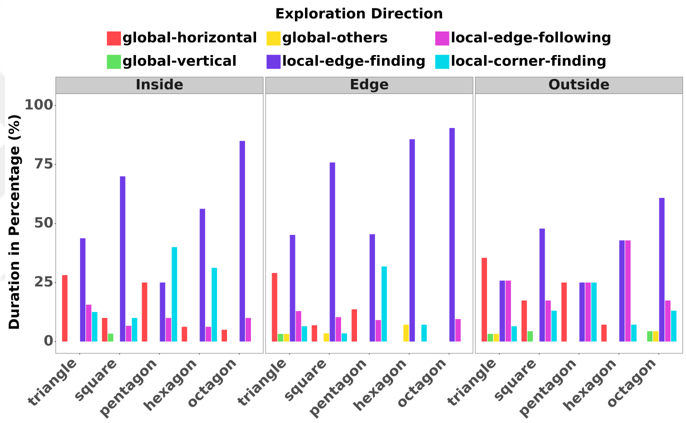
- Most participants ended their exploration by local-edge-finding (55%) (see the purple-colored bars in Figure 4.9b).

- The most explored strategy was local-edge-finding (32%) followed by local-corner-finding (21%) for all shapes and rendering conditions (see the purple and cyan colored bars in Figure 4.9c).

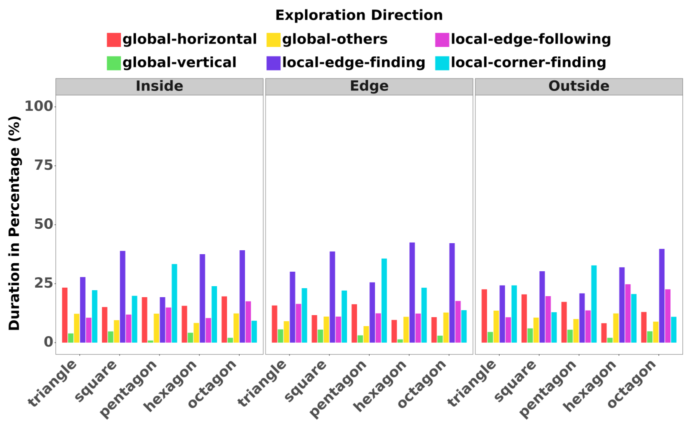
- The global scanning with exploratory direction vertical (3%) was the least explored strategy for all shapes and rendering conditions (see the green colored bars in Figure 4.9c).



(a)



(b)



(c)

Figure 4.9: Starting (a), ending strategies (b), and most/least explored (c) strategies and directions for all participants.

We observed that most participants followed a particular strategy while exploring the shapes. Initially, they explored the whole area inside the outer circle and then focused on the key features to identify the rendered shape. Overall, they spent less time in global scanning and more time in local scanning to identify each shape (Figure 4.10). As the shape gets complicated (i.e., the number of edges increases), the participants spent more time scanning the local features to identify the rendered shape correctly.

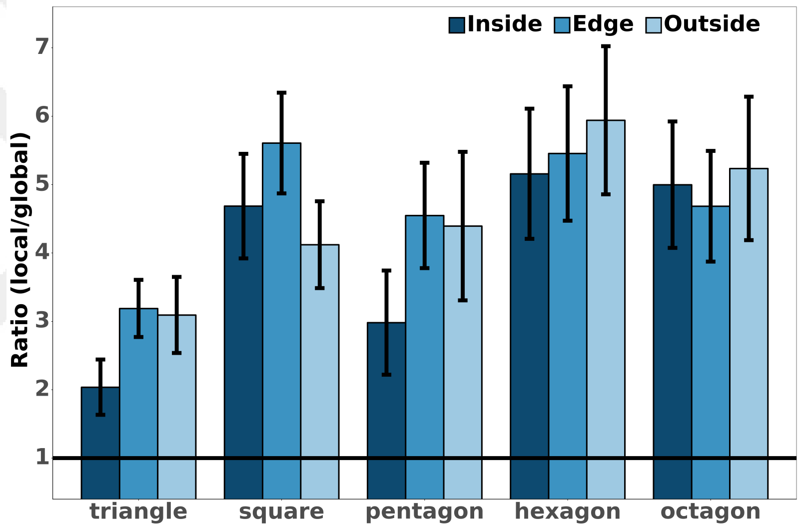


Figure 4.10: The ratio of local scanning time to the global scanning time for all five shapes under three rendering conditions. The horizontal solid line shows the boundary when the ratio is equal to one.

4.3 Experiment-II

The results of our first experiment suggested a perceptual bias in recognition of the shapes as they were displayed to the participants in prototypical orientation. We hypothesised that this is the reason why participants achieved a higher recognition accuracy for octagon than hexagon. To test this hypothesis, we conducted a second experiment with the same shapes but applied CW and CCW angular perturbations to change their orientation (with respect to the prototypical orientation) in order to reduce the perceptual bias (see Figure 4.11). We selected *Inside* rendering condition for the second experiment since the recognition time for *Inside* rendering condition was significantly shorter than the other two rendering conditions.

4.3.1 Participants

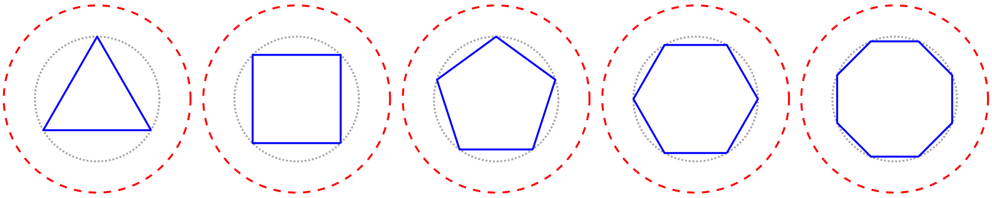
Nine different participants (5 male, 4 female with an average age of 26 ± 6.7 years) participated in the experiment. All of them were graduate students. The participants read and signed a consent form before the experiment, which was approved by the Ethical Committee for Human Participants of Koç University.

4.3.2 Stimuli

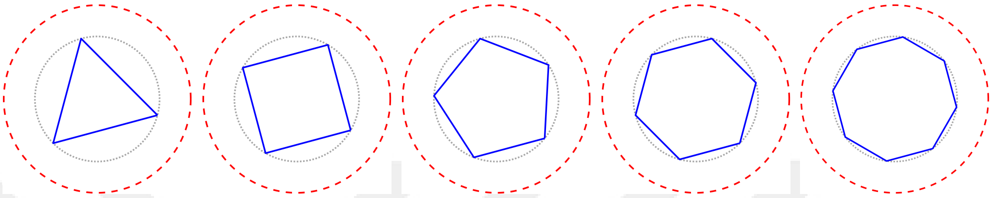
The experimental stimuli comprised five tactile shapes (triangle, square, pentagon, hexagon, and octagon) varying in orientation as shown in Figure 4.11. As suggested by [Theurel et al., 2012], the shapes displayed without any angular perturbation are labeled as "prototypical," and those displayed with angular perturbation are labeled as "non-prototypical." The non-prototypical shapes that are rotated by 15° about their geometrical centers in the counter-clockwise (clockwise) direction are called positive (negative). This angle was determined such that the resultant non-prototypical shapes did not resemble their prototypical counterparts when they were rotated (Note that the maximum value of rotation angle was 22.5° since a CCW/CW rotation of 22.5° applied to a prototypical octagon results in a prototypical octagon again).

4.3.3 Procedure

The experimental procedure for this experiment was the same as the first experiment. However, this experiment was performed in three separate sessions with one-day intervals between them. There were 30 trials in each session (5 shapes × 3 angular



(a)



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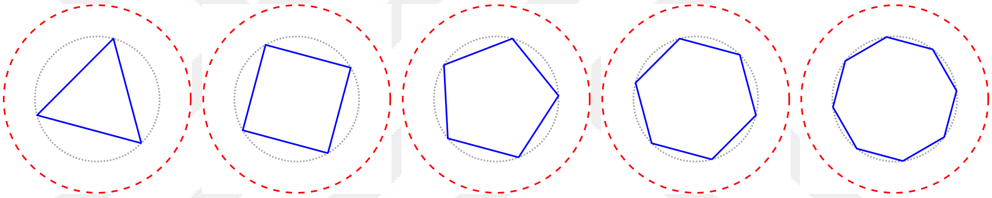


(c)

Figure 4.11: Five tactile shapes were displayed to the participants via electrovibration during the second experiment in three different orientations: (a) prototypical orientation, (b) CCW (+15°), and (c) CW (-15°) angular perturbations were applied to the prototypical shapes in (a) to construct the shapes in non-prototypical orientations.

perturbations × 2 repetitions). Hence, the total number of trials for each participant was 90. The trials were randomized while the same randomization pattern was used for all participants.

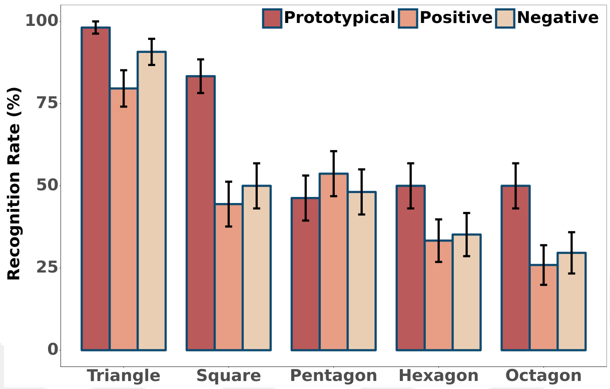
4.3.4 Analysis

This experiment was a within-subjects design with two independent variables; angular perturbation and number of edges. The analysis procedure was the same as the first experiment.

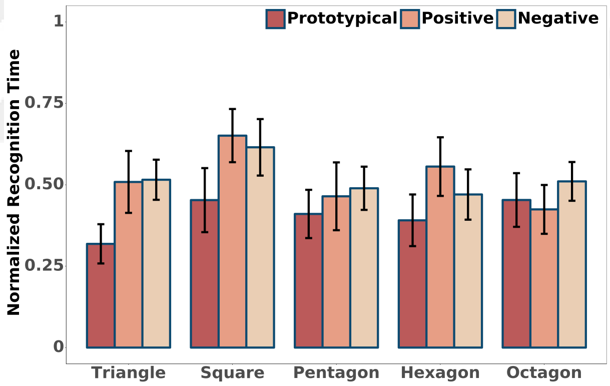
4.3.5 Results

Analysis of Recognition Rate and Time

Figure 4.12 shows the average recognition rate and recognition time of participants under three configurations (0°, +15°, -15°). Our results show that as the number of edges was increased, the recognition rate decreased significantly, more obvious for non-prototypical shapes than prototypical ones. We conducted a two-way with-in subjects MANOVA with two independent variables (angular configuration: prototypical, positive, and negative; number of edges: triangle (3), square (4), pentagon (5), hexagon (6) and octagon (8)) and two dependent variables (recognition rate and recognition time). The MANOVA found a significant main effect of angular orientation ($F(4, 32) = 4.248, p < 0.01, \eta^2 = 0.34$) and number of edges ($F(8, 64) = 9.749, p < 0.001, \eta^2 = 0.55$). The interaction effect between angular orientation and the number of edges was also significant ($F(16, 128) = 2.307, p < 0.01, \eta^2 = 0.22$). Individual ANOVA found a significant main effect of angular orientation on both recognition rate ($F(2, 16) = 10.473, p < 0.001, \eta^2 = 0.567$) and recognition time ($F(2, 16) = 8.130, p < 0.01, \eta^2 = 0.504$). The effect of number of edges was also significant on both recognition rate ($F(4, 32) = 30.823, p < 0.001, \eta^2 = 0.79$) and recognition time ($F(4, 32) = 3.682, p < 0.05, \eta^2 = 0.315$). Our post-hoc analysis of recognition rate showed that the statistical differences between prototypical and non-prototypical shapes significant ($p < 0.05$), supporting our hypothesis that there is a perceptual bias for prototypical shapes. Also, the statistical differences between positive and negative shapes were non-significant ($p = 1$). The recognition time was significantly smaller for the prototypical shapes as compared to the non-prototypical shapes ($p < 0.05$). However, the statistical difference between positive and negative shapes was again non-significant ($p > 0.05$).



(a)



(b)

Figure 4.12: Recognition rate (a) and normalized recognition time (b) for all shapes and angular orientations.

We also computed confusion matrices for the recognition rate (Figure 4.13). They show that as the number of edges increases, the recognition rate decreases significantly, especially for positive and negative configurations. Furthermore, as the number of edges increases, the confusion between the neighboring shapes also increases.

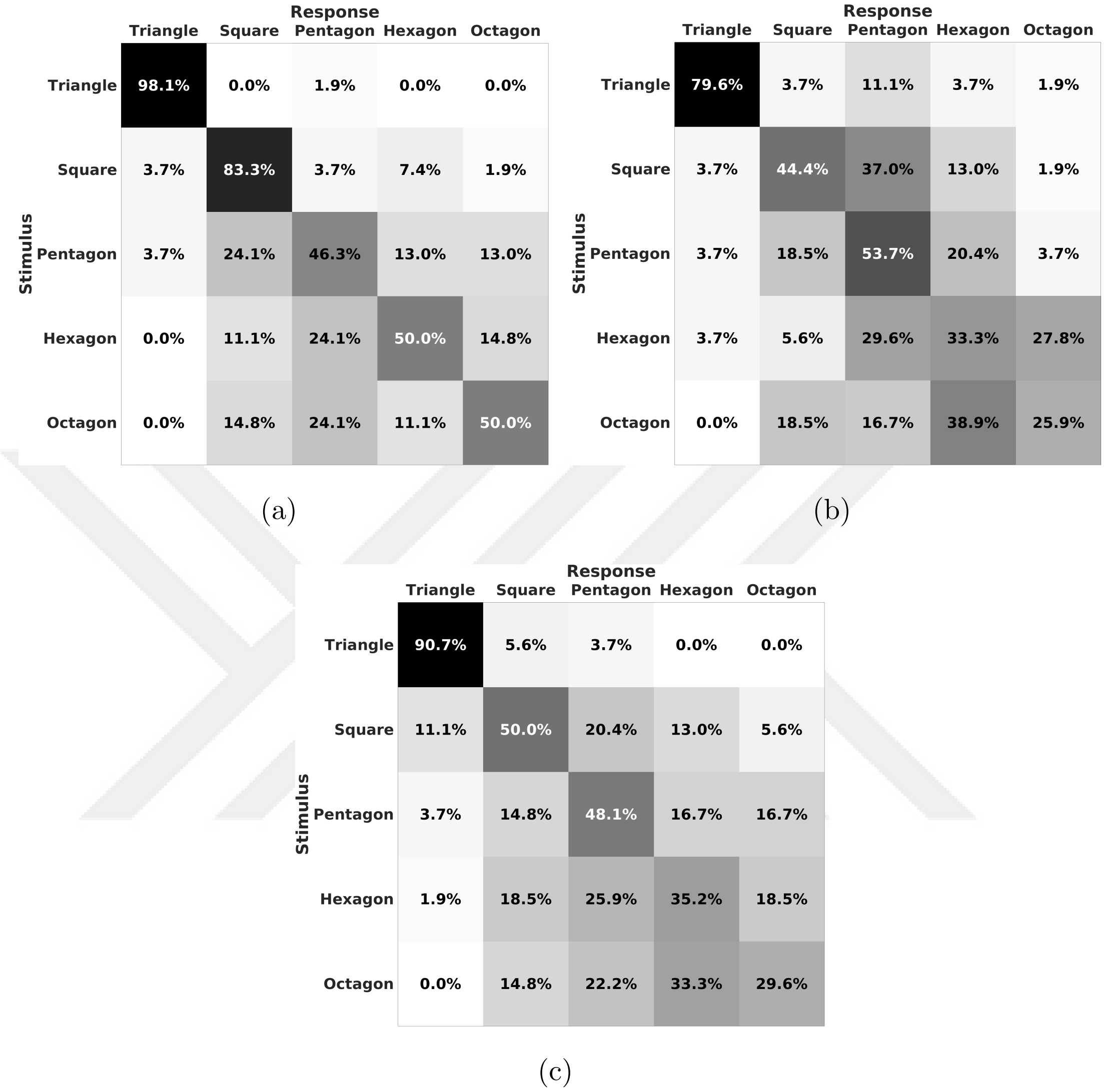


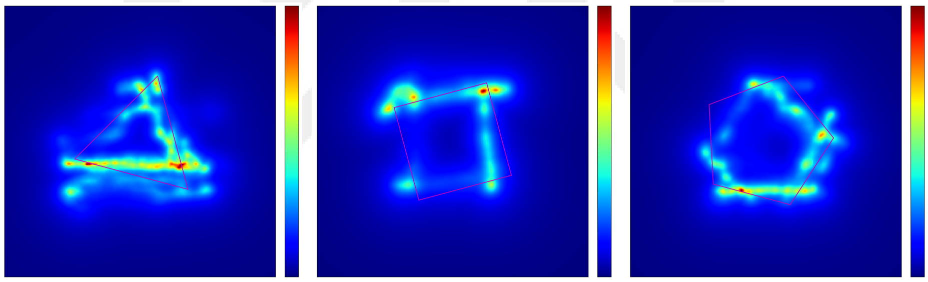
Figure 4.13: Confusion metrics of the recognition rate for prototypical shapes (a) and non-prototypical shapes; positive (b) and negative (c).

Spatial Analysis

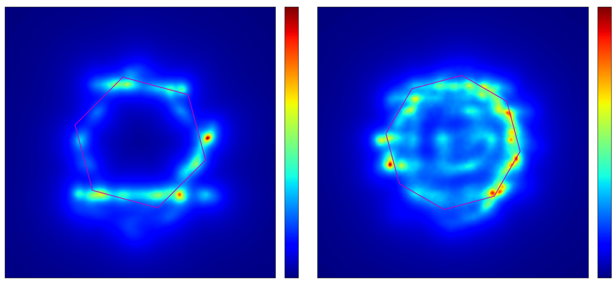
We calculated the number of times the participants touched the edges and corners of prototypical and non-prototypical shapes. A two-way MANOVA was carried out on the number of touches. We found a significant multivariate effect of angular orientation ($F(2, 114) = 5.744, p < 0.001, \eta^2 = 0.092$) and number of edges

$(F(4, 114) = 44.387, p < 0.001, \eta^2 = 0.609)$ on the number of touches. The interaction effect between angular orientation and number of edges was non-significant $(F(8, 114) = 1.958, p > 0.05, \eta^2 = 0.121)$. Our post-hoc analysis showed that the number of touches made to the corners and edges were not significantly different for all angular orientations and shapes except for square and hexagon. The number of touches to the corners (edges) was significantly higher (lower) for prototypical square and hexagon than their non-prototypical counterparts.

Figure 4.14 shows the frequency maps of participants for the perturbed shapes. Interestingly, we observed that participants scanned the non-prototypical shapes as if they were scanning the prototypical shapes, demonstrating again a perceptual bias for the prototypical shapes.



(a) Negative Triangle (b) Positive Square (c) Negative Pentagon

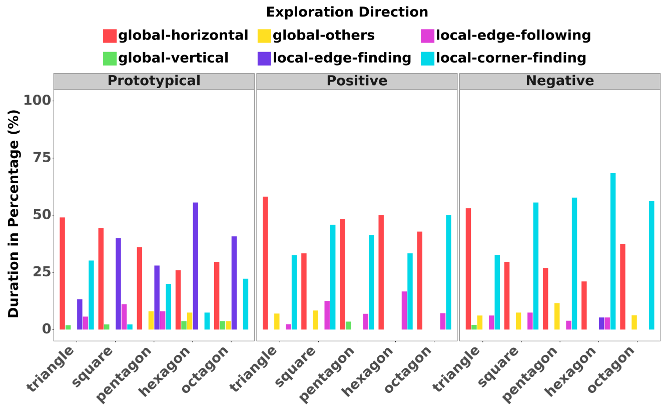


(d) Negative Hexagon (e) Positive Octagon

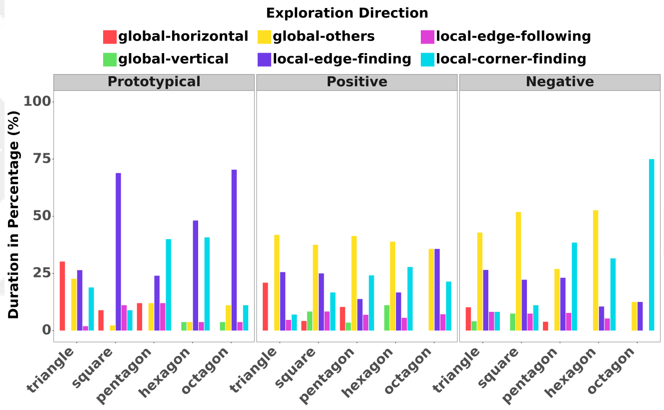
Figure 4.14: Frequency maps of randomly selected trials of participants for perturbed shapes.

Temporal Analysis

We investigated the scanning strategies used by the participants to explore the virtual shapes displayed on the touch surface. Our results showed that the most common starting strategy adopted by the participants was global scanning with exploratory movement as horizontal for the prototypical (37%) and the positive (46%) shapes and local-corner-finding (54%) for the negative shapes (Figure 4.15a). Participants have ended their exploration with local-edge-finding (47.57%) for the prototypical shapes and global-others (39%) for the non-prototypical shapes (Figure 4.15b). The most common exploration strategy was local-edge-finding (38.28%) followed by local-corner-finding (29.31%) for the prototypical shapes and local-corner-finding (38%) for the non-prototypical shapes followed by local-edge-finding (22%) (Figure 4.15c). The least explored strategy was global-vertical for both the prototypical (3%) and non-prototypical shapes (2%).



(a)



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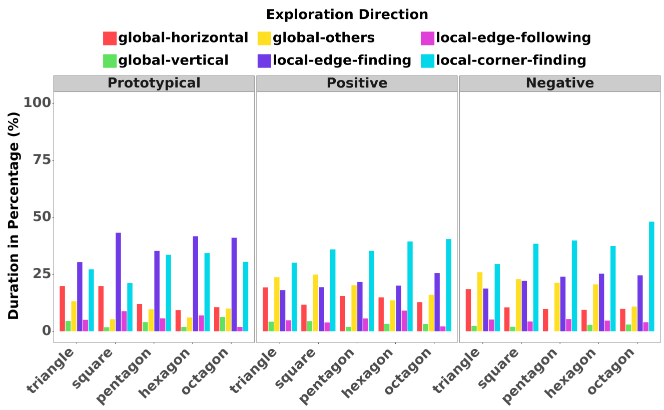

(c)

Figure 4.15: (a) Starting (a), ending (b), and most/least explored (c) strategies utilized for prototypical and non-prototypical shapes for all participants.

We observed that participants utilized global scanning first and then focused on the local features to identify the prototypical shapes. However, for the case of non-prototypical shapes, they started with global scanning, then focused on the local features, and finally performed global scanning again to confirm their decision.

We also observed that participants spent most of their exploration time on scanning the local features to identify the shapes. This observation can be further confirmed by Figure 4.16. As the number of edges was increased, it was more difficult for the participants to identify the shapes, and hence, they relied on the local features more to distinguish them.

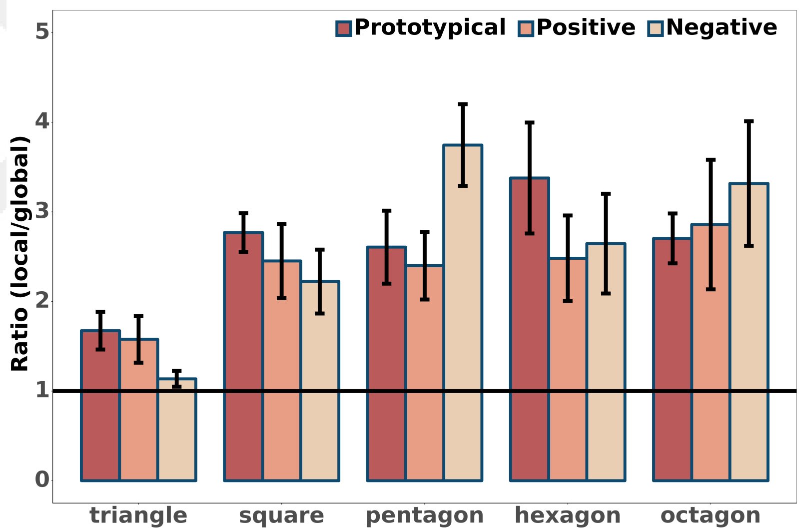

Figure 4.16: The ratio of exploration time spent for local scanning to global scanning for prototypical and non-prototypical shapes.

4.4 Discussion

In this study, we first investigated the effects of (a) number of edges, (b) rendering conditions, and (c) angular orientation on recognition accuracy and recognition time of the 2D equilateral geometrical shapes displayed by electrovibration on a touchscreen. Then, we investigated the exploration strategies followed by the participants to explore these shapes by analyzing their finger position recorded as a function of time.

4.4.1 Complexity of Geometry Affects the Tactile Perception of Virtual 2D Shapes

The results of Experiment-I showed that recognition rate was inversely proportional to the number of edges (except for octagon), and recognition time was directly proportional to the number of edges. Our analysis suggested that participants utilized the same scanning patterns to explore the shapes that looked alike and therefore confused them. For example, the top and bottom edges of prototypical hexagon and octagon are similar and parallel to the horizontal axis. The main difference between these geometries is on their left and right sides. Simply speaking, the displayed shape is a hexagon (octagon), when there is a corner (edge) on each side. The participants had difficulty in differentiating shapes using such local features as the geometric complexity was increased. Despite this difficulty, the participants were better in recognizing octagon than hexagon, which we believe was due to some perceptual bias.

In fact, the results of Experiment-II confirmed the perceptual bias reported in Experiment-I. We observed that the recognition rate for all non-prototypical shapes dropped significantly as the number of edges was increased. Triangle (3) had the highest recognition rate, while octagon (8) had the lowest. Considering the confusion matrices for the non-prototypical shapes (Figure 4.13b, 4.13c), we speculate that displaying more than five edges makes the recognition task highly difficult since false negatives was greater than true positives for the shapes higher than five edges (hexagon, octagon). As the number of edges in a shape increases, it becomes more difficult to form a mental image of the shape due to the amount of information that has to be processed in the brain, limiting the ability to identify the shape correctly. [Tennison and Gorlewicz, 2016] reported that participants could identify 2D shapes with up to four edges when they were rendered by vibrotactile actuators.

The participants in our second experiment achieved higher recognition rates in shorter recognition time for the prototypical shapes than the non-prototypical ones due to the mental rotation effect [Shepard and Metzler, 1971]. Similar results were also reported in the literature for the mental rotation experiments conducted with different types of stimuli [Milivojevic et al., 2011, Theurel et al., 2012, Zeugin et al., 2017, Tivadar et al., 2019]. [Theurel et al., 2012] also observed a prototype effect in their experiments conducted with congenitally blind and blindfolded adolescents on the haptic recognition of geometrical shapes. The authors suggested that the early exposure of the participants to these prototypical shapes in their visual environment was the leading cause of this effect. The lower recognition rate and longer recognition time of non-prototypical shapes also linked to the fact that participants exhibited difficulty tracing edges of the tactile shapes and detecting their orientation when they deviated from the horizontal and vertical orientation [Giudice et al., 2012, Palani and Giudice, 2014, Gershon et al., 2016].

4.4.2 Size of Haptically Active Area Affects the Tactile Perception of Virtual 2D Shapes

The results of our first experiment showed that participants spent less time recognizing the prototypical shapes when they were rendered by using *Inside* condition. Frequency maps for the shapes in Figure 4.8 highlighted that participants explored the corners and edges to identify the prototypical shapes. By inspection, we can say that they formed a decision about the shape that they were exploring after the third or fourth edge. They focused on exploring the edges during *Inside* and *Outside* rendering conditions and the corners in the case of *Edge* rendering condition to identify the rendered shape.

Participants achieved the shortest recognition time under *Inside* rendering condition. This result suggests that a larger haptically active area (where the electrovibration is on) leads to shorter recognition time. However, a good balance between haptically active and inactive areas must be maintained as suggested by [Gorlewicz et al., 2020]. They report that too much mechanical vibration on the touchscreen results in confusion and too little makes the interpretation of the tactile graphics challenging. Therefore, haptics application designers should guide the users by designating haptically active and inactive areas. For example, in our experiments, we guided the participants towards the haptically active area by visually displaying a circle with a diameter of 15 cm around the rendered shape. As a result, it was more easier for the participants to explore the designated area and identify the rendered shape. All our shapes fitted into an invisible circle of 10 cm in diameter, which was large enough for the participants to recognize them correctly.

4.4.3 Haptic Exploratory Procedures for Tactile Shapes

We observed differences in exploration strategies employed by the participants for the prototypical and non-prototypical shapes. Our analyses demonstrated that participants initially started their exploration with global scanning for both the prototypical and non-prototypical shapes to get an overall idea about the examined shape. They then switched to local scanning to discover its key features distinguishing the rendered shape from the other alternatives. For the prototypical shapes, they focused more on the edge-finding strategy. Possibly, it was easy for the participants to find and count the edges of the shapes at typical orientations. However, for the non-prototypical shapes, participants employed a corner-finding strategy because it was challenging for them to follow the edges. Furthermore, we observed that participants eventually performed another global scanning at the end of exploration for the non-prototypical shapes to confirm their decision. Similar strategies have been reported by [Bara, 2014] for the exploration of tactile pictures in a real book by visually impaired children. They reported that lateral motion was the preferred strategy to obtain global information about the shapes, and contour-following was opted by the children to perceive them accurately. [Simonnet and Vieilledent, 2012] and [Bardot et al., 2019] referred to the initial exploration of tactile maps, where participants obtained the overall idea about the map, as the investigation or discovery phase. When participants explored the maps in a particular way by following some specific strategies to complete the given task, they called this as the memorization phase. [Tennison and Gorlewicz, 2016] and [Gorlewicz et al., 2020] mentioned that users employed *"circling a part of a line"* strategy to determine the number and orientation of intersecting lines. This strategy was similar to the local-corner-finding strategy used by the participants in our study.

Frequency maps in Figure 4.14 revealed an interesting finding. The fingers of most participants in our second experiment traced the non-prototypical shapes as if they were scanning the prototypical ones. One potential reason is the perceptual bias for the prototypical shapes as mentioned before. Participants could have formed a spatial representation of each prototypical shape when visual feedback was provided to them during the training session. Although the shapes were not displayed visually during the actual experiments, participants traced the shapes using their index finger based on the information stored in their spatial memory. We believe that current limitations of the electrovibration technology also contributed to this behavior. Since SA-I receptors in fingerpad, responsible for detecting changes in static pressure, cannot be stimulated by electrovibration [İşleyen et al., 2019], the participants had to make zig-zag movements along an edge to follow it, which was not easy especially for the non-prototypical shapes. The temporal analysis also showed that edge-following was the least preferred strategy among the participants for both the prototypical and non-prototypical shapes.

Chapter 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

This thesis presented a new approach for rendering realistic button click sensation and investigated the strategies utilized by the participants to explore tactile graphics on touchscreens using surface haptics technologies. The motivation behind this work comes from the increased usage of touchscreen devices such as smartphones, tablets, kiosks, ATMs etc. in our daily routine. Although technological advancements have improved the quality of such devices, their usefulness remains confined to basic user interactions with limited tactile feedback to the user. Currently, these surfaces can generate only monotonic vibrations in response to users' actions. However, it is possible to display programmable and more sophisticated tactile feedback using surface haptics techniques, which is necessary for more natural and intuitive interaction.

In chapter 3, we investigated how to create tactile feedback on touchscreens that simulates the feelings of physical buttons. Although pressing and turning on/off a button is a simple physical interaction in our daily life, imitating it in a digital world, especially on touchscreens, appears to be more difficult. In fact, this is not surprising if we look at this simple physical interaction more carefully. First, our experimental data of acceleration and force quickly reveals that each button has distinct response characteristics (see Figure 3.7). Second, the identification of sub-events and their timing are important (for example, the *Latch Button* in our study is activated in two stages with a certain time interval between them, see Figure 3.7). Third, the instant of button activation with respect to the acceleration profile is critical for proper rendering of digital buttons on touchscreens (again, for example, *Latch Button* is activated quite late compared to others, see Figure 3.7). When humans interact with the physical buttons in the real world, they receive kinesthetic haptic feedback, which is not possible yet to replicate in the digital world on a touchscreen. Currently, only tactile haptic feedback can be displayed through a touchscreen in the form of vibrotactile stimulus as it is done in this study or friction modulation via ultrasonic or electrostatic actuation as in other studies conducted in our research laboratory [Saleem et al., 2018, Vardar et al., 2017b, Vardar et al., 2018]. Hence, for example, it is highly difficult to convey the springiness of a physical button via tactile feedback on a touchscreen (*Push Button* in our study is a good example of this case).

Moreover, humans are good at controlling force in their daily interactions with physical objects, and buttons are no exception for this. For example, we know exactly how much pressure to apply to turn on/off a light switch in the real world. In particular, the accumulated pressure is related to the activation and deactivation instant and period of a button. It is also important to note here that there are also differences between the magnitude of force/pressure applied by the individuals (see Figure 3.8). Since it is highly difficult to measure contact forces in systems utilizing a touch surface, the earlier studies have mostly ignored the role of accumulated force/pressure in tactile rendering of digital buttons. In our study, we relate finger contact force with the contact area and activate a digital button based on the instantaneous finger contact area of the participant, which is measured by an infrared camera during real-time interaction. The digital button is activated when the participant applies sufficient pressure to the touchscreen with her/his finger such that the instantaneous contact area exceeds the pre-determined threshold value.

Even though we paid attention to the details discussed above in order to imitate the feelings of physical buttons realistically, our results show that participants were able to match digital buttons with their physical counterparts on only four adjective pairs. This might be related to the kinesthetic feedback displayed by the physical buttons and also their physical dimensions and surface textures, which may affect the pressure distribution and friction on the finger. Also, we were not able to stimulate all the mechanoreceptors that were stimulated when interacting with the physical buttons. For example, (Slow Adapting) SA-I is responsible for detection of edges, intensity, and pressure which was not stimulated when interacting with the digital buttons.

In chapter 4, we investigated how participants explore tactile shapes on touch surfaces under electrovibration. In particular, we investigated the complexity of displayed geometry and the size of haptically active area on perception of tactile shapes as well as the haptic exploratory procedures that enable to perceive them. In addition to measuring recognition rate and time, we performed spatial and temporal analyses on the collected finger position data in order to investigate the exploratory strategies.

We observed that the recognition rate is inversely proportional to the complexity of shape. As the number of edges was increased, it became more difficult for the participants to recognize the tactile shape rendered by electrovibration. Our results showed that rendering 2D shapes with more than five edges causes the recognition rate to drop significantly and become unreliable (the true positives were less than the false negatives).

Furthermore, our results showed that the size of the haptically active area affects the perception of shape. Participants in our experiments were able to identify the displayed shapes faster when the haptically active area was larger, as in *Inside* rendering condition. In *Edge* rendering condition, there were many white spaces (haptically inactive areas), and therefore, participants spent the longest time for recognizing the shapes. They had to depend on the corners during *Edge* rendering condition owing to the fact that the haptically active area was smaller, and it was not easy to detect/follow the edges of the shapes. As a result, participants counted the corners (or the number of intersecting edges) by circling around them.

Analysis of exploration strategies exhibited that participants did not rely on a single strategy to explore the shapes. Moreover, they employed different exploration procedures for the prototypical and non-prototypical shapes. They started their exploration with global scanning to identify the shapes' global features and then switched to local scanning to focus on the shape's key features for the exploration of prototypical shapes. However, in the case of non-prototypical shapes, they performed an additional global scanning at the end of exploration to confirm their decision. We also found that participants preferred the corner-finding over the edge-finding for the non-prototypical shapes because it was challenging to detect and follow the tilted edges of those shapes compared to detecting their corners. Tactile masking techniques could be utilized to increase tactile contrast and make the detection of edges easier as suggested in [Vardar et al., 2018], but following them would still be challenging. Here, it should be noted again that the exploration of 2D shapes embossed on a paper stimulates (Slow-Adapting) SA-I receptors, which is not possible under electrovibration. These receptors are primarily responsible for detecting changes in static pressure in normal direction, which enables us to detect edges of real shapes and objects easily. This also makes it possible to follow the edges/contours of real shapes and objects even when no visual feedback is available. However, edge-following was the least preferred local exploration strategy by the participants in our study since electrovibration modulates frictional forces in tangential direction only and hence the participants had to make zig-zag movements to follow an edge (i.e. they could not stay on the edge).

5.2 Future Work

5.2.1 Rendering Variety of Digital Widgets

In our thesis, we focused on the tactile rendering of digital buttons based on the data originating from their physical counterparts using vibrotactile actuation on a touchscreen. In the future, we will focus on the haptic display of a variety of digital widgets such as slider and knob by replicating the distinct response characteristics of their physical counterparts.

5.2.2 Multi-Modal Systems

In this thesis, we first utilized vibrotactile actuation to render digital buttons and then electrovibration to render tactile shapes on touch surfaces. In the future, we will investigate the benefits of multi-modal approach in tactile rendering by integrating electrovibration with electromechanical actuation on a single platform. For example, it is possible to display multi-modal tactile feedback (vibration in the normal direction and friction force in the tangential direction) for rendering digital slider and knob. Once these digital controls are designed, and tested through user studies, they can be integrated into various applications such as gaming, education, and data visualization.

5.2.3 Rendering of Digital Buttons on Different Locations

In this thesis, we rendered the digital buttons on a fixed location using one piezo patch (PA) on HapTable. However, investigating the change in tactile perception when these digital buttons are rendered on different locations using different resonance frequencies on the HapTable would be an interesting future work.

5.2.4 Tactile Shapes using Multi-Finger

In this thesis, our second study was limited to a single point of contact during exploration of tactile shapes on a touchscreen. Investigation of the exploration strategies employed by the users while exploring tactile shapes on a multitouch interaction surface requires another comprehensive research study. This multi-finger approach may lead to more accurate and faster recognition of virtual shapes.

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