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Katrin Wolf

Grasp Interaction with Tablets

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Contents

Abstract

Two trends currently change the way people interact with computers. First, tablets are forecasted to outpace the sales rates of computers in 2015 (The Telegraph 2014). Secondly, the possibility to interact with handheld devices on the back side will extend current touchscreen interaction and allow novel ways to interact with mobile computers. For both new trends, tablet interaction and back-of-device interaction, no guidelines exist that face the ergonomic differences between tablets and phones and between front- and back-of-device interactions.

This thesis develops guidelines for a future device type: a tablet that allows ergonomic front- and back-of-device interaction. These guidelines are derived from empirical studies and developed to fit the users' skills to the way the novel device type is held.

Three particular research areas that are relevant to develop design guidelines for tablet interaction are investigated: *ergonomic gestures*, *interaction areas*, and *pointing techniques*.

In order to provide a repertoire of gestures for tablet interaction that are feasible while keeping the device grip stable, 21 gestures are developed. This repertoire is designed and evaluated by experts in physiotherapy and sport science. It provides gestures that are easily feasible while grasping and serves as input for the following investigations. The gestures of this repertoire that are most promising for tablet interaction are further investigated in a user study. Parameters for gesture detection are identified and thresholds that allow developers to distinguish touch gestures from unintended touches are derived.

Research on interaction areas is motivated by two aspects: understanding where interaction areas are unintentionally touched when tablets are held as well as defining areas that are in reach for the established direct touch interaction. These topics were addressed through user studies. The results show that the areas that are unintentionally touched and the areas that are used for gestures overlap. Moreover, a shortcoming of direct touch interaction, which is reaching the center of both, the front and the back of the tablet, was analyzed. The dimensions of the area that is in reach while grasping a tablet are precisely described. Furthermore, design recommendations to overcome the poor accessibility of the center area are given.

To overcome the limited accessibility of tablets' center area, two experiments were conducted. The first provides an understanding of the biomechanical limitations of direct touch. It is shown that the easiest reachable positions for direct touch are where digits have a relaxed pose and are neither completely stretched nor fully bended. The second experiment compares three indirect pointing techniques with direct touch. Design guidelines are recommended that allow designers to consider the entire interaction area of tablet devices on both, the front and back sides without limiting the usability of widgets in the center.

The main contributions of this dissertation are concentrated in a set of guidelines for the design of handheld tablet devices' interfaces on both device sides. These guidelines will help designers and developers of user interfaces to build ergonomic applications for tablet devices, in particular for devices that enable back-of-device interaction. Furthermore, manufacturers of tablet devices obtain arguments that back-of-device interaction is a promising extension of the interaction design space and results in increased input capabilities, enriched design possibilities, and proven usability.

Chapter 1
Introduction

Recent years have seen a fundamental shift in how people interact with computers.

With the rise of mobile phones, mobile interaction became the predominant way people interact with computers; and it has even been expected that they may replace the traditional desktop computer (Baudisch 2010).

Smartphones, which already outpaced PCs in number of sold devices (Fig. 1.1) allow not only a broad range of mobile communication, such as phone calls, email, and video chat; they also allow users to play games, browse the internet and offer functionalities of existing devices, such as cameras, alarm clocks, and navigation systems. As phones are carried around all day; researchers assumed that mobile devices will shrink and become extremely small to increase usability as they fit in small pockets and are lightweight (Baudisch and Chu 2009).

More recently, another mobile device type gained huge market success: tablet ownership has grown rapidly over the last years. Tablets, which in 2015 are expected to outsell PCs (Fig. 1.1), have much in common with mobile phones and seem to be just larger. The extent in size, however, influences the usage of tablets. While mobile phones are used everywhere, on the go, in the office, in trains, as well as at school underneath the table and hidden from the teachers' eyes; tablets are —due to their size—used less often in mobile scenarios. A recent study showed that tablets are most often used on the couch or in the bed for checking email and playing games (Müller et al. 2012).

The development of smaller and thus portable computing system started in 1972 when Alan Kay proposed a concept of one of the first portable devices, the *Dynabook* (Kay 1972). It had already about the size of a modern tablet PC; and it was intended to satisfy key requirements of mobile computing. Through including a display, allowing for touch input, displaying dynamic graphics, the *Dynabook* was designed to enable applications, such as audio recording and office tasks with storage and pervasive network connectivity. Kay also discussed the idea of a touchscreen through proposing the option of either providing a physical keyboard or having a large display that covers the entire front and provides an on-screen keyboard. Thus, the *Dynabook* anticipated the concept of current tablet devices and

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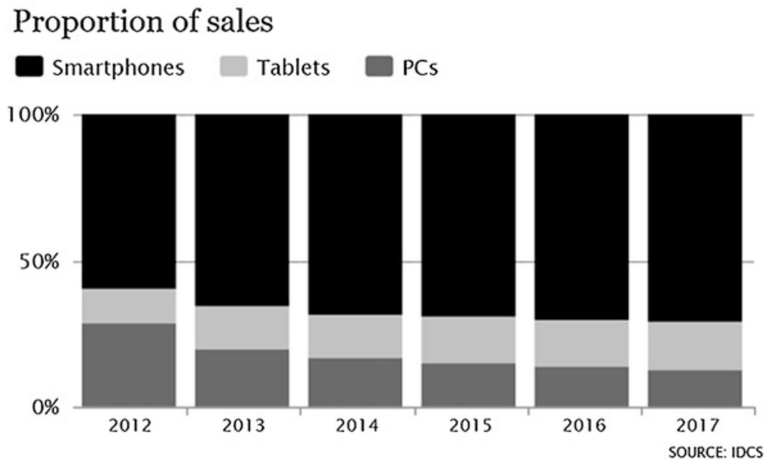

Fig. 1.1 Sales in 2013: smartphones: 65.71 %, tablets: 14.61 %, PC: 20.22 %; and sales forecast 2015: smartphones: 69.04 %, tablets: 15.86 %, PC: 15.1 % (taken from The Telegraph 2014)

influenced their form factor as well as the general input on touch-sensitive displays, even though they are just available to the mass consumer market since devices like the Palm Pilot (1997), the Microsoft Tablet PC (2001) and first *iPad* generation (2010) were released.

Accordingly, main concepts of human-tablet interaction are similar to those for mobile phones; and the phone interface was simply adapted. The design concepts for mobile phone interaction have been developed to fit mobile computing and on-the-go interaction. These scenarios, however, differ significantly from those of tablet devices (Müller et al. 2012). On one hand one may suggest that more ergonomic interactions lead to more mobile use cases for tablet devices. On the other hand typical tablet use cases, such as couch and bed environments are very different from those of phones, Thus, simply reusing the design guidelines developed for mobile phones for tablet devices is not sufficient. Design guidelines that do not fit the characteristics of tablets cannot offer the optimal usability. Therefore, there is a need for design guidelines that support interaction designers and developers in designing applications that especially fit for tablet devices.

This thesis focuses on developing guidelines that not only consider the specific characteristics of tablet devices but also the user's physiological skills for allowing designers and programmers to develop ergonomic tablet interactions. It considers the form factor of tablet devices, how these devices are held, and what limitations are given by the biomechanics of the hands.

The approach of this thesis is to develop design guidelines for tablet devices by understanding and exploiting the underlying human factors. The aim is to gain knowledge about users' abilities to execute gestures while grasping a tablet and to provide guidelines that allow interaction designers and developers to design grasp-based tablet interactions that fit to users' needs and abilities.

1.1 Scope of the Thesis

There are many ways to grasp a tablet and these completely change the gestures that are executable.

In Microsoft's (2012) user experience guidelines for tablet devices, four grips are listed to be most commonly used.

Two grips are resting the tablet on a table or the legs. They are hands-free, non-mobile, and not in the scope of gesture interaction with grasping hands. The third grip is a one hand holding, while the other hand is "free" for interacting. While the "free" hand has good access to the entire touchscreen, holding the device with one hand can be tiring. Furthermore, holding the device with one hand decreases the stability of the grasp as an increase in distance between hand root and device balance point negatively influences interaction performance (Wagner et al. 2012). In terms of mobility, the forth grip is most adequate as two hands are holding the tablet in landscape format (Fig. 1.2).

This grip allows both hands to interact with the device. Moreover, the grasp is more stable than if the device is held with one hand only. The symmetric two-handed grip was empirically identified to be the best-performing grip for tablets (Oulasvirta et al. 2013). It has most ergonomic advantages for mobile and standing use cases; this grip is very appropriate for tablet interactions as it allows for stably holding tablets while interacting with them. Interacting while keeping a grip enables both thumbs for interacting on the touchscreen. Such a grip also supports back-of-

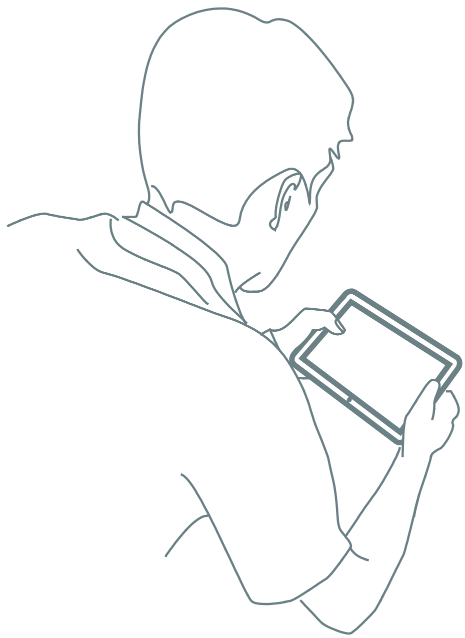

Fig. 1.2 Symmetric bimanual tablet grip

device interaction proposed by Wigdor et al. (2007) and built in consumer devices since 2012 (Sony Vita); allowing fingers to interact on the rear without releasing the device grip.

This thesis focuses on the two-handed grip of tablets held in landscape format. The two-handed grip allows for gestures that are executed with the digits of the grasping hand without releasing a hand. Gestures that are executed with the digits of the grasping hand are considered. These gestures will, due to the two-handed grip, be located at the front as well as at the back of the device. Device movements and other input modalities, such as gaze and speech are excluded of the scope of this thesis.

This thesis investigates how interactions with tablet devices should be designed in order to fit to human skills and technical possibilities. Here, existing technologies as well as new trends will be considered. That includes embedded touchscreens that are already used for gesture detection.

Mobile devices with a touch-sensitive back side are commercially available. It can be expected that touchpads will soon be embedded in the back of many devices. Front-of-device interaction cannot simply be adapted for interaction on the back. Design guidelines for back-of-device interaction are missing. This thesis provides them for interactions with tablets held in both hands.

In summary, the scope covers touch gestures of all digits that are executed with both hands while holding a tablet in landscape format.

1.2 Challenges in Tablet Interaction Design for Grasping Hands

Interaction design for tablet devices can build upon research on mobile phone interaction. While technologies for gesture recognition using touchscreens are adapted, some characteristics of grasp-based tablet interaction, which are for instance gesture interactions executed with the hands that hold the device, require a different interaction design than what is used for mobile phones. Two of these characteristics are the form factor of tablets and the possibility to execute gestures while holding the device. These two challenges are outlined in the following.

1.2.1 Form Factor

The form factor is a combination of a device's size, shape, and style, as well as the layout and position of the device's major components. The shape, style and layout of phones and tablets are similar; but the weight and the size of both devices are significantly different.

The heavier weight of tablets changes the way the devices are held; and a symmetric bimanual grip is proposed to ensure a stable grasp (Oulasvirta et al. 2013). Moreover, pointing performance with the grasping hand depends on the distance between hand root and device balance point (Wagner et al. 2012), which is different for tablets versus mobile phones. This challenges the design of gestures that are feasible while holding a tablet.

The larger size of tablets compared to mobile phones directly influences the interaction area as this area is covering almost the entire front and, for back-of-device interaction, potentially also the entire rear side. While the hands grasp the device; the center of a tablet is not accessible for releasing touch events (Odell and Chandrasekaran 2012). This is in line with Microsoft's (2012) design guidelines. They mention that anything in the middle of the tablet screen is difficult to reach and requires changing posture, if the device is held with both hands. The worse accessibility of the center is especially relevant for defining the layout of a graphical user interface, such as the positions of buttons and other widgets. Users need to reach these widgets through direct touch or other pointing techniques to be able to interact with the device and to control applications. Thus, pointing techniques that allow the user to access the entire interaction area is a key topic addressed this work.

1.2.2 Grasp-Based Front- and Back-of-Device Interaction

The thumbs can perform gestures on the touchscreen while holding a tablet with both hands. Furthermore, the fingers that are rested on the device's rear enable back-of-device interaction, as proposed by Wigdor et al. (2007). Today, a number of devices are available that have a touchpad on their rear side (e.g. Sony Vita and the Motorola CHARM). As fingers have different characteristics and vary in their ergonomics compared to the thumb; ergonomics of front-of-device interaction with tablets are different from those of back-of-device interaction. This interaction style has to be investigated separately and understood to develop an interaction design that fits to the specific challenges of ergonomic grasp-based interaction.

1.2.3 Resulting Research Topics

The form factor and the bimanual grip make it hard to reach widgets in the center of the device. Thus, both aspects challenge the design of grasp-based tablets interactions.

A shown in Fig. 1.3, the digits' reach and grasp constrain the gesture design space (A). The thumb is better feasible than the fingers because it has one more degree of freedom at its bottom joint. Moreover, the device may rest on the fingers while being held, which limits the fingers' reach even more.

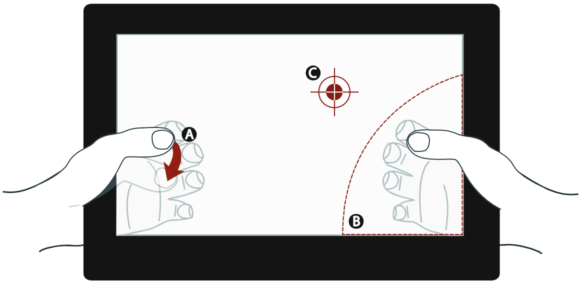

Fig. 1.3 Tablets that is grasped with a symmetric bimanual grip and highlighting of the three major research topics that are addressed in this thesis: (*A*) gestures that are executable with grasping hands, (*B*) interaction areas that are accessible while grasping, and (*C*) pointing techniques that allows for selecting targets at the entire interaction area, also out of the accessible regions

The form factor influences the interaction area of the touchscreen as well as of touchpads that may be embedded in the rear of the device. Fig. 1.3 shows that the lengths of the digits may limit the area that is accessible to perform touch-based gestures or to select targets (B).

As target acquisition through direct touch is restricted by hand size, targets in the center of the screen may not be reached, as shown in Fig 1.3(C). That lack of interaction area accessibility requires alternative techniques for target acquisition beyond direct touch.

In summary, investigations that address each of these design aspects, which are ergonomic gesture design, the definition of interaction areas on the front as well as on the back of tablets, and pointing techniques that enable access to the entire interaction areas are needed. Investigation and solutions for these three key design aspects define the research topics of this thesis.

1.3 Research Contributions

This dissertation contributes to the field of human-computer interaction and investigates grasp-based interactions with tablets with a focus on ergonomics.

The main contributions of this thesis are (1) an ergonomic gesture repertoire for grasp-based interaction and (2) guidelines for implementing touch gestures, which relate to the first research topic of ergonomic gesture design. The second research topic of accessible interaction areas contributes to (3) interaction area diagrams for the front and the rear of tablets devices. Investigations of the third research topic of pointing techniques results in two contributions: (4) fundamentals in the hands' biomechanics while pointing with direct touch and (5) guidelines for designing grasp-based pointing techniques for tablets that allow for accessing the entire interaction areas. The five contributions are explained in the following part.

(1) The ergonomic gesture repertoire consists of 21 gestures that are feasible while grasping objects that are held with all three main grasp types palm, pad, and side grasp. The gesture repertoire is designed and evaluated by experts in physiotherapy and sport science. It provides gestures that are easily feasible while grasping that serve as gestures for the following investigations and can also serve as a repertoire for other designers and developers when designing grasp-based interaction.

(2) The implementation guidelines for touch gestures contain diagrams, which indicate at what interaction areas the four most promising gestures of the repertoire (tap, press, drag, and swipe) are executed on both tablet sides while the device is held with two hands. Thresholds for gesture implementation are provided. These can be used for gesture implementation and also allow for identifying a touch of a finger that is resting on the back of a tablet while holding the device. That information helps to avoid misinterpretations of gestures by the computing system.

(3) Interaction areas for both tablet sides are presented in diagrams and compared with areas that are touched unintentionally while holding a tablet with both hands. This enables interaction designers to make decisions about the GUI layout and identify situations where pointing at GUI components via direct touch is not appropriate.

(4) Insights about the performance of direct touch at interaction areas on both the front and the back of a tablet are provided. Fundamentals in the biomechanics, in particular joint motions and flexion of the thumb and the index finger while pointing at targets are presented. That allows for instance understanding why targets that are located close to the palm are harder to select than those a bit further away. Moreover, insights on limitations of pointing via direct touch for targets that are located in the center are given.

(5) Guidelines for designing pointing techniques that overcome the shortcoming of direct touch in grasp-based interaction are provided. The guidelines are based on empirical investigations where the direct and indirect pointing techniques are compared against each other regarding their performance as well as their usability.

1.4 Dissertation Structure

This dissertation is structured to emphasize the contributions highlighted above.

In Chap. 2, *related works* are presented in order to provide an overview of the state of the art in ergonomic gesture design, in defining interaction areas as well as in pointing techniques, in particular for hand-held devices. It is highlighted how the contributions of this dissertation build upon or extend previous work in the field.

In Chap. 3, *ergonomic gestures for grasp-based interaction* are identified and evaluated. An expert-generated ergonomic grasp-based gesture repertoire is identified as a base for later investigations of specific grasp-based gesture execution and interaction. This chapter provides the following information: (1) a generic gesture repertoire for interacting with grasped devices and (2) an expert evaluation of the feasibility of each gesture as well as highlighted feasibility limitations.

In Chap. 4, *parameters for gesture implementations* are defined through recording prototypical gestures in a user study. These parameters are compared with established gesture parameters that are for example used for Android gesture detection. The design guidelines presented in this chapter include parameters for prototypical touch-based gestures, in particular touch, press, drag, and swipe, on both, the front and the back of a held tablet, such as positions on the device, path length, velocity, and expectable durations.

In Chap. 5, *areas for front- and back-of-tablet interaction* are identified through user studies. First, unintended touch events are explored. Secondly, the areas on the front and on the back of a tablet that are easily accessible through touch while holding are determined; and ergonomic constraints imposed by grasp and the digit length are explored. The findings highlight appropriate interaction areas of both sides of a tablet, which are defined by the accessibility of the surface of tablets. These are compared with interaction layouts recommended for touchscreen of *Windows* 8 tablets. Additionally, improved interaction areas based on the evaluation of users' abilities to access surface regions of both tablet sides are introduced.

In Chap. 6, *insights into direct touch pointing* are provided to address the problem, presented in Chap. 5, of accessing the center of the device. A pointing study is presented to provide deeper insight about pointing on tablets through direct touch.

In Chap. 7, *an understanding about direct and indirect pointing techniques* for grasp-based tablet interaction is provided. In a user study, direct and indirect pointing techniques are compared with each other to analyze their performance and their usability. Limitations of direct touch with hand-held tablets are investigated with the aim to identify appropriate techniques that allow for reaching targets on the entire interaction area, also in the center of the device. The findings of the study are concluded in design recommendations for pointing techniques with tablets that are held in two hands.

In Chap. 8, the design guidelines of all previous chapters are summarized; and in Chap. 9, the dissertation is *concluded* by summarizing and contextualizing the contributions and discussing their implications for the field of mobile human-computer interaction.

Chapter 2
Related Work

Research on interaction with tablets is rare compared to work that is done on interaction with mobile phones. Two major challenges in grasp-based tablet interaction are to consider the influence of the form factor and of the grasp on ergonomics in interaction design. Ergonomics in interactions design affects the gesture design, the accessibility of interaction areas, and pointing at targets that are hardly accessible through the common direct touch. As such, relevant works on *ergonomics in gesture design*, the definitions of *interaction areas*, and *pointing techniques* for tablets are presented in the following sections.

2.1 Ergonomics in Gesture Interaction with Grasping Hand

Designing gestures that are easy for the computer to recognize, as well as easy for the user to remember and perform, is difficult. While gesture interfaces often may be constrained through the possibilities of sensor technology (Bailly et al. 2012; Gustafson et al. 2010); a large body of work applied a user-centered design approach. A common approach in user-centered gesture design is to *enable the user to design gestures* for specific predefined commands (Bhandari and Lim 2008; Kray et al. 2010; Wobbrock et al. 2009). Whilst other researchers have investigated *ergonomics in gesture interaction* to better understand why certain gestures are easier to perform than others (Hoggan et al. 2013; Wobbrock et al. 2008), with a goal to develop design recommendations for easier performable gestures.

2.1.1 Gesture Design

Besides technology driven gesture design (Han 2007; Bailly et al. 2013), a common method in gesture design is to ask participants to design gestures or to select ones from given examples that they find being an appropriate fit to predefined commands.

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Bhandari and Lim (2008) asked participants to design gestures to common camera control and picture view tasks. They identified a collection of touch-based gestures, such as tap, drag, pressure and drawn circles and squares, as well as gestures that require moving the mobile phone, such as shaking the phone to start a slide show. Wobbrock et al. (2009) investigated user-defined gestures for tabletops by asking participants to propose gestures for a given task without providing any guidance on what those gestures should be. Kühnel et al. (2011) adapt the design methodology proposed by Wobbrock et al. (2009) for the development of a gesture-based user interface to a smart-home system. The authors show the adaptability of the approach described by Wobbrock et al. (2009) for three-dimensional gestures in the smart-home domain. Kray et al. (2010) conducted a study to identify user-defined gestures for connecting mobile phones, public displays, and tabletops, e.g. to synchronize devices or to download content from one to another. Wolf et al. (2011a) explored the development of mobile device gestures (touch gestures on a phone as well as device movements) to control a spatial auditory interface by asking users to propose and design gestures for given tasks. Results showed a set of 20 touch and motion gestures to control the auditory interface.

The sets of the user-defined gestures contain mainly commonly known touch gestures, such as tap and drag, some more symbolic gestures drawn on the touchscreen, such as a cross, as well as device movements, such as pointing with the device at objects or directions or tilting and rotating it. All gestures are quite simple and easy to perform. They are known from HCI, have analogies to inter-human communication, and are mostly deictic or symbolic gestures (Rime and Schiaratura 1991), such as pointing at content to select it or crossing out something to disconnect or delete it. Fewer gesture are iconic sighs, for instance, shaking a device to activate it refers to shaking somebody to wake him/her up.

The main focus of these works is rather an analysis about the gesture-functionality mapping than as if participants would have designed gestures that are ergonomic. All presented user-defined gesture sets mainly contain gestures that are commonly known from gesture-based human-computer interaction or from inter-human interaction. While the user-design gestures may be subconsciously chosen because they are easy to remember and easy to perform, the design decisions participants make during that approach is mostly hidden, and as such not evaluated. One may suggest that some participants chose gestures that they already know, because the majority of the chosen touch gestures are gestures that are listed in the Apple Design Guidelines (Apple Inc. 2013), as well as in those from Android (Android Developers Gesture Patterns 2013) and in the Windows UX Guidelines (Microsoft 2012).

2.1.2 Ergonomics in Gesture Execution

However, much research has been done in designing gesture interaction; work on ergonomics in that area has just recently begun to address diverse ergonomic aspects in gesture execution, such as muscular load, fatigue, performance, gesture execution time and gesture execution paths.

Tomatis et al. (2012) used electromyography (EMG) to investigate gesture ergonomics, in particular muscular load during tapping tasks. Lozano et al. (2011) obtained finger movement (angular excursions of the finger joints) information with a CyberGlove® 22 sensor system; and the data of finger movements followed the same trend as EMG and thus showed that more finger movements cause higher muscular load. They showed through considering EMG in addition to a data glove, that hand configuration affects ergonomics of multi-touch gestures.

Assuming ergonomic gestures lead to high performance, in particular short task solution times and few errors, Wobbrock et al. (2008) compared the performance of the index finger and the thumb for front- and back-of-phone interactions, and showed that with shorter interaction times, when using the thumb on the front screen, interaction has greater ergonomic values than e.g. interacting with the thumb on the rear of the phone.

Hoggan et al. (2013) investigated ergonomics for touch gestures that are executed with a "free" hand on a tablet. They found that rotation gestures with two touches are differently executed depending on their starting points. Parameters of a rotation gesture were systematically controlled in the experiment, such as rotation angle, rotation direction, distance between fingers, and position. Time and touch events were recorded; and the variations for each factor were controlled by giving instructions to the participants. The study shows that within-gesture parameters, such as the angle of the fingers (given as start and final position of the two touch points) influence the gesture execution time.

Wolf et al. (2012a) explored touch gesture parameters in gestures for back-of-device interaction with mobile phones. Gestures are often guided through visual feedback as it is usually provided through slider shapes and button positions. Wolf et al. asked participants to perform one-hand gestures on the back of mobile phones without providing guidance. They found that gesture trajectories differ depending on the location they are performed at, between the fingers that execute the gesture, and in regard to its direction. For example, a prototypical drag path performed with the index finger is significantly longer than one performed with the ring finger. Thus, a drag gesture for touchscreen gestures may require different thresholds for gesture classification than if the gesture is performed on a touchpad on the back of the device. Furthermore, grasp-based gestures are not performed with a free hand in contrast to typical gestures on mobile phones.

However, the act of grasping (i.e., prehension) has been widely studied (Jones and Lederman 2006; MacKenzie and Iberall 1994) to understand the hand's biomechanics and the way people grasp objects, gesture ergonomics of grasping hands is rarely investigated, and no work has been done in exploring gesture ergonomics while grasping tablets.

2.1.3 Summary

The grasp seriously constrains touch gesture execution on tablets because it limits the flexibility of the hand. Thus, ergonomic gestures are needed for that interaction scenario. The approach of user-defined gesture design shows what gestures are familiar and preferred by users than result in ergonomic gesture design. However, ergonomics are considered when existing gestures are evaluated in regards the specification of particular parameters; ergonomics has not been considered during the gesture design process so far.

Thus, considering ergonomics in the gesture design process for grasp-based interaction is a true research gap, which this dissertation will address in Chap. 3. In Chap. 4 it is presented how parameters of the ergonomic gestures are more specifically defined.

2.2 Interaction Areas

Reachable interaction areas for tablet devices are recommended in the user experience guidelines from Microsoft (2012). However, interaction areas for the most common ways to hold the device are proposed; for the two-handed tablet grip in landscape format (which this dissertation focuses on) it is recommended to readjust the grip for accessing the center of the device. Thus, no interaction areas for the symmetric bimanual grip (Fig. 1.1) are defined by Microsoft.

Odell and Chandrasekaran (2012) investigated the interaction areas of the symmetric two-handed grip and found that the center of the tablet is not reachable. Participants were asked to draw with finger paint on paper attached to a tablet's touchscreen sized 286 × 183 × 14 mm while holding it with two hands. No paint was drawn in the center of the tablet. Unfortunately Odell and Chandrasekaran provided no precise dimensions for the accessible touch areas. Thus, the existing guidelines for interaction areas are rather roughly defined.

However, research on tablet interaction areas is still limited to the touchscreens built in the front side of the device; using the back side of tablets for interaction is a promising direction to extend tablets' interaction areas. The technology company Apple filed a patent on back-of-device interaction in 2006 (Kerr et al. 2010); and Wigdor et al. (2007) demonstrated in 2007 how back-of-device interaction when using a tablet-sized device solves the *fat-finger problem* (Siek et al. 2005). Since the release of the Motorola CHARM in 2010 and the Sony Vita in 2012, mobile devices with a touch-sensitive back are commercially available. It can be expected that touchpads will soon be embedded in the back of many devices. Previous research did not address back-of-device interaction areas on tablet devices and consequently, corresponding design guidelines are not available. Thus, the accessibility of interaction areas for grasp-based interaction with two-handed held tablets, including the front and the back of the device, are the second major research topic of this dissertation. This topic is addressed in Chap. 5.

2.3 Pointing Techniques

The limited accessibility of interaction areas on tablets indicates the problem of accessing items that are not located within these areas. That motivates research toward understanding of pointing on tablets. The aim is to overcome the current limitations caused by the limited target accessibility in the center of both sides of tablets. Research on pointing on tablet devices has to the author's best knowledge not been done and thus is a research gap. Thus, general works on pointing with hand-held devices is presented here, which includes mobile phones. Four categories of pointing techniques have been identified while researching relevant works on this topic: direct touch pointing, inverse direct pointing, remote direct pointing using a miniature interaction area, and relative pointing. These four categories are used as structure of the follow sections.

2.3.1 Direct Touch Pointing

Direct pointing is known to be very immediate and intuitive as touching the desired target refers to the way people interact in the physical world. In contrast to the physical world however, virtual targets are often very small. That causes the *fat-finger-problem* (Siek et al. 2005), which means that the finger that touches the target is occluding it, which decreases precision. *LucidTouch* (Wigdor et al. 2007) is a tablet-sized device that enables back-of-device interaction; and thus the fingers can select targets from the back side without occluding the content that is displayed on the front. *LucidTouch* uses a camera mounted at the rear of the device, which results in a rather bulky prototype. Thus, the concept of back-of-device interaction has been improved by Baudisch and Cheng: *NanoTouch* (Baudisch and Cheng 2009) uses a back-mounted touchpad instead of a camera and thus enables back-of-device interactions even with very small devices.

If a user holds the device while pointing, the hand has to solve multiple tasks and direct pointing becomes more challenging due to the hand's bio-mechanics. Thus, in addition to occlusion, a second problem of direct touch is the accessibility of targets that are further away or very close. The center of the tablet is hard to reach if the device is held in landscape format with both hands (Odell and Chandrasekaran 2012). Moreover, for one-handed pointing on mobile phones it was found that the thumb performance varies with its posture. Poorest pointing performances result from excessive thumb flexion. When tapping on targets closest to the base of the thumb in the bottom right corner of the screen the performance is low. The highest performance is achieved when the thumb is in a rested posture, neither significantly flexed nor fully extended (Trudeau et al. 2012).

2.3.2 Inverse Direct Pointing

Roudaut et al. (2008) introduced *MagStick*, which is a thumb interaction technique for target acquisition on mobile devices with small touch-screens. The technique addresses screen accessibility as well as target selection accuracy and occlusion. The user controls a cursor through an inverse drag motion and thus can select a target without occluding it with the thumb. While *MagStick* enables access to a larger area than the thumb can reach via direct touch, Roudeau et al. found that it is slower.

Kim et al. (2012) proposed an expandable cursor called *Large Touch* that also moves inversely to the user's finger. In contrast to *MagStick*, the cursor moves a larger distance than the thumb that slides across the touchscreen. Thereby, *Large Touch* enables to reach locations that are further away from the thumb. Also in contrast to Roudaut et al., Kim et al. found no difference in target selection time between the inverse cursor technique (*Large Touch*) and the common direct touch technique in a conducted study.

2.3.3 Miniature Interaction Area

Karlson and Bederson (2007) introduced *ThumbSpace* that allows for one-handed thumb interaction for small targets that are spread out wide on mobile phones' screens, which is similar to the problem of pointing on targets that are, due to the size of a tablet, hard to reach. This problem was solved by shrinking the screen into a small screen that is defined by drawing it with the thumb. That ensures that the thumb can reach all targets. Thus, *ThumbSpace* improves accuracy for selecting targets that are out of thumb reach; but it is slower than target selections with direct touch. A similar concept was proposed by Kim et al. (2012) who presented *Sliding-screen* to address the limited target accessibility on phones' touchscreens. A drag from the edge of the screen towards the screen's center dynamically shrinks the interaction area. Then a tap can easily reach targets on the smaller display that may have been too far away on the interaction area before shrinking it. This technique was, like *ThumbSpace*, found to be slower than direct touch for one-handed target selections with mobile phones.

The *ARC-Pad* (McCallum and Irani 2009) links the touchscreen of a phone to a large display in a one-to-one mapping. It enables to use the phone's touchscreen as absolute and as relative touchpad for large displays. *ARC-Pad* combined absolute and relative cursor positioning. Tapping on the *ARC-Pad* causes the cursor to jump to the corresponding location on the screen, providing rapid movement across large distances. For fine position control, users can use a relative cursor control technique.

2.3.4 Relative Pointing

Relative pointing is often used for remote-selections, such as mouse and touchpads that are built in laptops. Forlines et al. (2007) compared direct touch versus mouse input for unimanual and bimanual tasks on tabletop displays. Analyzes of quantitative performance and subjective preference indicate that users may be better off using a mouse for unimanual input and their fingers for bimanual input when working on a large, horizontal display. Cockburn et al. (2012) compared performance in touch selections on a touchscreen that was horizontally placed on a table in front of the user. They found that direct touch is faster than relative pointing (tap is faster than drag) using the finger. The error rate is high for small targets and further increases using direct pointing methods for target acquisitions over longer distances.

Hasan et al. (2012) compared relative pointing with direct touch for back-of-device interaction. They found that relative pointing is faster and more accurate on the back of the device.

A comparison of *ARC-Pad* (McCallum and Irani 2009) with relative pointing showed that *ARC-Pad* is faster than relative pointing. Moreover, relative pointing was more accurate. Thus, the *ARC-Pad* was, just like direct touch usually is, faster but less accurate than relative pointing.

2.3.5 Summary

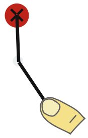
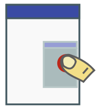
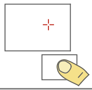
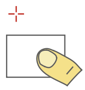
Previous work developed and compared pointing techniques for tabletop displays (Forlines et al. 2007; Cockburn et al. 2012), for mobile phone touchscreens (Karlson and Bederson 2007; Kim et al. 2012; Roudeau et al. 2008; McCallum and Irani 2009), and for the backside of phones (Hasan et al. 2012). Tablets are, however, a third device type that, except from this dissertation, has almost been neglected. Their size and weight requires a certain grip that not only affects pointing performance but also makes parts of the screen inaccessible using direct touch.

In pointing research with mobile phones, direct touch was in comparative studies always found to be the fastest technique; while it suffers from accuracy and occlusion as well as from constrained accessibility for targets that are further away. Other techniques are slower but allow for accessing target over larger distance.

In summary, no research was done in investigating direct touch pointing on tablets, neither on the touchscreen nor on the back of the device. Furthermore, the problem of reaching targets in the center of the device through investigating techniques beyond direct touch is a research gap. Identifying a pointing technique for targets out of reach is an important research topic for bimanual tablet interaction as the established direct touch technique fails.

In Chaps. 6 and 7 these research gaps are reduced through two controlled experiments, one on understanding biomechanics in pointing with direct touch and another in comparing four target pointing techniques, which represent the four categories discussed above. Both studies consider front- as well as back-of-tablet

Table 2.1 Comparison of the features of different pointing techniques (extension of Roudaut et al. 2008)

	Direct touch	Inverse cursor	Miniature area	Relative pointing (touchpad)
Example	Common touchscreens: 	*MagStick*: 	*ThumbSpace*:  *ARC-Pad*: 	Common mousepads: 
Target accessibility	Within the length of the digits	High	Everywhere	High
Occlusion	Everywhere	None	*ThumbSpace*: everywhere; *ARC-Pad*: none	None
Pointing accuracy	Coarse	Fine (if facilitated by magnetic cursor)	Less accurate than relative pointing	Fine
Target acquisition time	Fast	Slower than direct touch	Slower than direct touch (*ThumbSpace*; faster than relative pointing (*ARC-Pad*)	Slow

interaction. Chapter 6 provides a fundamental understanding of direct touch pointing on tablets with grasping hands. In Chap. 7 it is shown that indirect pointing techniques enable to reach targets that are not accessible through direct touch; and the usability of these techniques is discussed (Table 2.1).

2.4 Summary and Resulting Research Questions

This dissertation focuses on grasp-based interactions with tablets; and guidelines that support designing interactions with these devices are missing. Research gaps exist for instance in guidelines for touch gestures considering both, touchscreen gestures as well as back-of-device gestures. Furthermore, interaction areas have been investigated for tablet devices; but the information gained there are vague and again, the back of the device has not been addressed. Finally, research on pointing techniques for tablet devices is important, as the accessibility of the interaction areas are limited. As no previous work addressed this topic; this dissertation investigates the limits of direct touch for pointing at tablets as well as compares pointing techniques that are designed with the aim to reach targets that are not reachable with direct touch while grasping a tablet.

Chapter 3
An Ergonomic Gesture Repertoire for Grasp-Based Interaction

This chapter provides an ergonomic grasp-based gesture repertoire. That is created by experts and serves as base for later investigations of grasp-based gesture execution and interaction that are presented in Chaps. 4–6.

Hands have many degrees of freedom and allow for an infinite number of poses and movements. In mobile computing, devices are mostly held while being used; and gestural interaction is either realized with the "free" hand that does not hold the device or with the hand that is holding it. The second scenario described grasp-based interaction, which is the research topic of this thesis. This chapter focuses on the ergonomic design of gestures for grasp-based interactions that can be performed with the grasping hand.

Researchers have indicated that scientific knowledge about gesture interaction is still limited but is beginning to address the human factors of gesture execution (Zhai et al. 2012). In that sense, gesture design considering human factors shall be ergonomic and thus suite with the abilities and motor constraints of the human hand as well as of the limitations given by grasping a device or an object.

Traditional manual tools, such as of scissors or cutlery, have form factors that are influenced by the anatomy and feasible movements of the human hand. Similar, in this chapter a generic gesture design will be generated that is influenced by the motions a hand can easily perform; and the limitations of the gesture design are given by constrains of the grasping hand as well as through biomechanical limitations of the hand's movability.

Taxonomies about the grasping hand (MacKenzie and Iberall 1994), grasp types (Feix et al. 2009), hand sizes and joint flexibility (Lange and Windel 2006; Luttgens and Hamilton 1997) exist. However, these taxonomies were generated with the purpose to support the design of everyday objects as well as prosthesis; none of the ergonomic works mentioned above covers finger and hand movements that are executed in parallel with grasping.

As such a taxonomy would be a valuable contribution for designing ergonomic gestures for interacting with hand-held devices, namely grasp-based interaction; this chapter seeks to provide insights in ergonomics of gesture execution while grasping. After providing relevant insights in hand biomechanics and grasp ergonomics, an ergonomic gesture vocabulary defined by experts will be presented, the gestures will

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be evaluated regarding aspects relevant for ergonomic grasp-based interaction, and relevant work in gesture detecting interfaces will be discussed to decide which technology will be used as apparatus in further research on grasp-based interaction.

3.1 Biomechanical and Grasp-Based Constraints

3.1.1 Biomechanical Constraints

The hand has 26 degrees of freedom (Vardy 1998) as shown in Fig. 3.1a. Each two upper joints of a digit has one degree of freedom (DOF), while the lowest finger joint has two and those from the thumb has three DOF. Vardy (1998) also considers two DOF for the wrist and three DOF for the entire hand. Each digit joint allows for being flexed up to 110° (defined by Nielsen et al. (2003) and shown in Fig. 3.1b). Thus, in theory the possibilities for designing gestures are extremely high. In practice, biomechanical constrains limit the design space for gestures that are finger movements a lot. Therefore, understanding biomechanics of the hand provides a fundamental grounding for research on gestural interaction design, as due to biomechanical constraints some gestures are easier performable than others, while some may not be feasible at al.

For example, it is impossible to bend all joints separately to a desired degree within the possible ranges per digit shown in Fig. 3.1b. Furthermore due to tendon

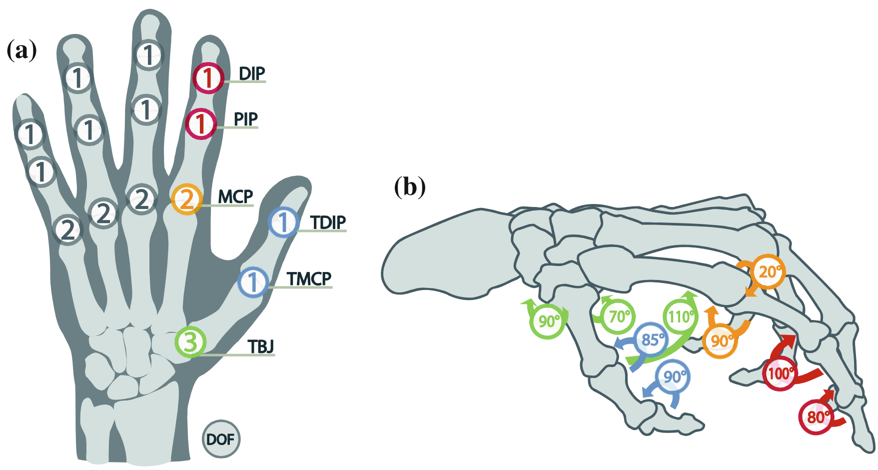


Fig. 3.1 **a** Human hand with joint names and degrees of freedom (DOF). **b** Hand from side with finger flexibility. The thumb has three joints: the thumb basal joint (TBJ), the thumb metacarpophalangeal joint (TMCP), and the thumb distal interphalangeal joint (TDIP). The joints of the fingers are metacarpophalangeal joint (MCP), the proximal interphalangeal joint (PIP), and the distal interphalangeal joint (DIP)

connections between the ring and middle finger (Spalteholz and Spanner 1960), it is almost impossible to bend the MCP joints of these fingers separately at the same time. Bending the ring finger will automatically result in bending other joints, e.g. those of the middle and little finger. Motion dependencies are known for joints of the same finger (*intra-finger dependencies*) as well as for joints of different fingers (*inter-finger dependencies*) and are described by Cobos et al. (2007).

Intra-finger dependencies occur for the upper two joints of each finger in a linear angular relationship (Hrabia et al. 2013[1]) that explains how much bending one joint causes bending the neighbor joint.

Furthermore, biomechanical constraints are given through *inter-finger dependencies*. That aspect is known from piano players who train moving their neighbor fingers separately for avoid coupling movements of fingers. But without training, people can hardly move all their fingers separately. That is according to Cobos et al. (2007) not the case for the index and middle finger. But when moving the ring finger, the middle and little fingers, generally execute automatically co-movements.

However, finger movability can increase with training; this work focuses on general movability as the aim of this thesis is to define design guidelines for gestural interaction for users in general and not for special skilled sub-groups.

Moreover, the scope of this work is not on mid-air gestures but on gestures executed by grasping hands. Thus, the design space for feasible gesture is additionally constrained by the grasp, for example, it may be important to keep certain fingers continuously adjusted in a certain pose. Therefore, in the next section, fundamentals of the grasping hand are presented, and relevant research questions are formulated according to that.

3.1.2 Grasp-Based Constraints

Grasping is a motor task that requires muscle contraction for bending fingers or for applying pressure towards the grasped object. If two motor tasks are performed at the same time with one hand, such as grasping and moving fingers for gesture execution, the physical load of the hand increases as both tasks, grasping and gesture execution, require manual work. However, this dissertation is motivated by the belief that both tasks can be solved in parallel, one grasp type may allow for executing a certain gesture while another may not.

In this section, literature on grasp classification (Feix et al. 2009) is presented and the manual resources taken by the grasp are discussed. This survey serves for formulating assumptions about spare manual recourses, which are not necessarily involved in grasping and thus potentially may be available for gesture execution.

[1] The work of Hrabia et al. (2013) is an outcome of a master thesis that was collaboratively supervised by the author and M. Wilhelm (TU Berlin, DAI Labor).

Feix et al. (2009) address both goals by analyzing 14 grasp taxonomies generate over more than 90 years of research on the human hand. They categorized three main grasp types that refer to 33 different sub-types. Table 3.1 shows the three main grasp types of Feix et al. (2009) that are: palm, pad, and side.

Each grasp type is exemplarily represented with a picture; and the motor resources that are required for these grasps are described in the third column of Table 3.1. Based on the inter-finger dependencies, information about indirectly involved fingers/digits is added by the author. Finally the digits, which may be capable for executing gesture with the grasping hand but without losing the grasp, are concluded. These potential movable digits while grasping are assumed through excluding from all digits those that necessarily are involved in the grasp as well as the fingers that cause inter-finger dependencies from them. The thumb causes no motions of the fingers and is completely independently movable.

Considering inter-finger dependencies, a finger can also be indirectly involved in a grasp if its muscle activation—because of intra-finger dependencies—would result from an actuation of a neighbor finger that actively is involved in grasping. That already shows that the ring finger may not be appropriate for performing gestures while grasping as explained beforehand.

One may assume that the movable digits while grasping differ for each grasp type (Table 3.1). For all grasp types, the thumb and at least one opposite finger is involved in grasping (Table 3.1, column 3). If the ring finger is not needed for grasping it might still be indirectly involved in grasping through inter-finger dependencies. For instance, if the middle finger is also grasping an object, the ring finger would not be independently bendable (Table 3.1, column 4).

That assumption leads to three questions that will be investigated in the expert interviews described in Sect. 3.2:

Q1: What motions of digits are feasible while grasping and thus, contribute to a generic grasp-based gesture vocabulary?
Q2: What digits are appropriate for gesture execution while grasping?
Q3: What situational parameters influence the appropriateness of a gesture?

3.2 Method

This dissertation focuses on grasp-based tablet interaction. The grasp serves here as starting point for searching executable gestures while grasping. Wimmer (2011) stated that there are many ways to grasp an object; and Feix et al. (2009) provides a grasp taxonomy that allows for distinguishing between three grasp types. While there are many ways to hold a tablet, the form factor of other objects as well as tasks that are performed with those can determine one specific grasp (Table 3.1). Thus, in the presented approach, rather than tablets, other objects are used that have a form factor that requires a specific grasp, such as a stylus, a steering wheel or an ATM card.

Table 3.1 Design space for grasp-based gestures: constraints and moveable digits while grasping with the three main grasp types: palm, side, and pad

Grasp type (Feix et al. 2009)	Example	Involved hand-parts (Feix et al. 2009)	Indirect involvement	Potentially movable digits
Palm	 Medium wrap	Low power grasp performed by 2-directional force between palm (finger 2–5) and abducted thumb that allows for been interrupted	None	While grasp: none While grasp interruption: all particular fingers and thumb
Side	 Precision grasp	2-directional force between: (a) Abducted thumb and index finger or (b) Abducted thumb, index and middle finger	(a) None (b) Ring finger	(a) Finger 3–5: middle, ring, and little finger (b) Little finger
Pad	 Dynamic tripod	2-directional force between: (a) Added thumb and middle finger while index finger stabilizes or (b) Thumb and index finger while middle finger stabilization	(a) and (b) ring finger	(a) and (b) little finger (a) Stabilizer: index finger

In expert interviews, the literature-based assumptions (Table 3.1) of feasible finger movements while grasping are defined in greater detail (published in Wolf et al. 2011b). For answering the research questions *Q1*, *Q2*, and *Q3* formulated in Sect. 3.1.2, interviews with experts in biomechanics have been conducted and thus, sports- and physiotherapists were acquired as they have deep insights in the movability of fingers and hands. Moreover, they are aware of problems that may occur when moving them repeatedly, e.g. when playing professionally a music instrument or using a computer mouse every day. The expert participation in the process of identifying a gesture repertoire guarantees that gestures are chosen with respect to the biomechanical constrains of the hand and it also ensures that frequent gesture execution does not cause problems but is easily feasible.

3.2.1 Design

An established method to design gestures for human-computer interaction is through user participation. For instance, tasks may be pre-defined and the participants are asked to find an appropriate gestures (Wobbrock et al. 2009; Wolf et al. 2011a). This method commonly intends to define intuitive gestures as participants rely on previous knowledge. However, intuitive function-gesture mappings are very useful for the ability of users to remember the gestures; designing ergonomic grasp-based gestures requires different gesture characteristics, such as the ability of the user to perform the gesture easily while keeping the grasp.

However, Wagner et al. (2012) and Oulasvirta et al. (2013) found that there are many ways to hold a tablet device; Feix et al. (1999), MacKenzie and Iberall (1994), and Aicher and Kuhn (1995) state that the grasp is influenced by the form and the function of the grasped object (Table 3.1). In fact there are shapes other than the one of tablets, which requires a specific ways to grip an object for using it. For instance a scissor allows for very little grasp modifications while cutting.

The aim of the expert interviews presented here is to identify gestures that are executable when holding a tablet device in many ways. Providing a gesture repertoire that is executable while holding objects in various ways and of different shapes would have the benefit to fit for future devices that are expected to vary in order to their form factors (Benko 2009; Roudaut et al. 2011).[2] To ensure to develop an as generic as possible gesture repertoire that is executable while grasping, three props are used that are typically grasped with the three main grasp types: palm, pad, and side. Moreover, for the interview props objects were chosen that have been used for human-computer interaction already, such as gestures on steering wheels (Döring et al. 2011) and on digital styluses (Song et al. 2011).

[2] That also serves as assumption in Wolf et al. (2013), where gesture input on variously shaped surfaces has been proposed by the author and some of the gestures of the generic vocabulary have been evaluated.

3.2.2 Task

During the interviews, the experts were asked to grasp the props and to pretend to use them is in a typical way (Fig. 3.2: steering wheel: driving, ATM card: inserting the card into an imaginary machine, and stylus: writing). Each prop requires a different grasp: A steering wheel determines mostly a palm grasp (Fig. 3.2a), a stylus a side grasp (Fig. 3.2b), and an ATM card is normally held through a pad grasp (Fig. 3.2c). This made sure the experts configured their hands according all grasp types and enables them to evaluate existing gestures and to create new ones. As starting point, an initial gesture set (Fig. 3.3) was created using gestures that were already proposed in works related to grasp-based interaction by Ashbrook (2010), Harrison et al. (2010), Howard and Howard (2001), Rekimoto (2001), Saponas et al. (2009) as well as Vardy et al. (1999).

3.2.3 Procedure

In the interviews, the experts (one sports therapist and three physiotherapists) were interviewed separately in two sessions. The first session started with a prepared set of 12 hand gestures (Fig. 3.3), which were graphically presented to be evaluated by the experts. This initial gesture set consisted of seven palm-gestures,

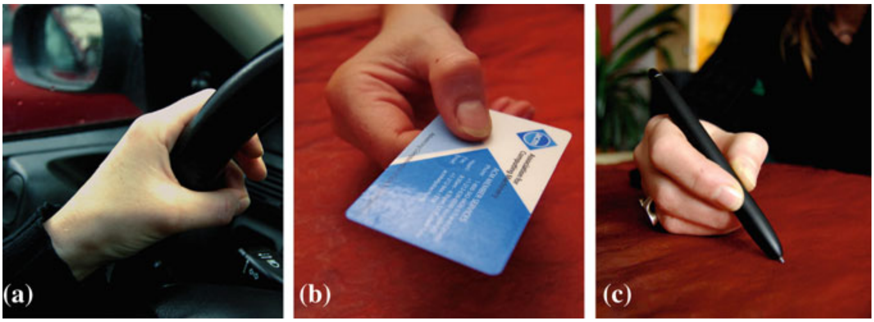


Fig. 3.2 Experts are testing the movability of given and self-designed hand gestures using props: **a** a steering wheel, **b** a chip card and **c** a stylus

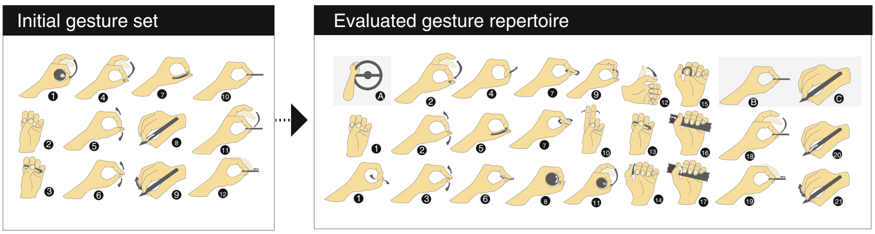


Fig. 3.3 Initial gesture set (*left*) that served as base to generate the final gesture repertoire (*right*)

two pad-gestures, and two side-gestures, which were already used within research projects about finger- and grasp-based gestures. The experts were asked to execute the gestures of the existing set with each prop (Fig. 3.2) and to add gestures they could also think of to be adequate for the given context.

For each gesture, the ones of the existing set as well as for the new collected ones, follow five interview questions—referring to the research questions *Q1*, *Q2*, and *Q3* (Sect. 3.1.2)—were answered by the experts:

Q1: What digit motions are feasible while grasping and thus, contribute to a generic grasp-based gesture vocabulary?

(1) *Gesture vocabulary*. Which gestures could you think of that are easily feasible while holding the prop?

Q2: What aspects enrich or constrain the ability for gesture execution while grasping?

(1) *Movability rating*. How easy is the hand gesture performable with each digit?
(2) *Limitations*. What ergonomic aspects limit the hand gesture performance?

Q3: What situational parameters influence the appropriateness of a gesture?

(1) *Midas touch problem.*[3] Could the gesture be randomly performed during the task and therefor provoke a risk of confusion with natural movements?
(2) *Context and task*. Could explain how well you think each task related to the prop is suitable to allow for interacting at the same time through gesture interaction?

3.2.4 Measurements

Gesture demonstrations (*Q1*) were recorded through video camera. The answers for *Q2*(*2*) were recorded in an open questionnaire. The rating for *Q2*(*1*) were ++, +, –, – –; whereby ++ means easily feasible and – – means hardly feasible. The ratings for the risk of accidentally released commands (*Q3*(*1*)), which refers to the Midas touch problem (Istance et al. 2008; Jacob 1990) were “high” and “low”; and explanations for the Midas touch problem as well as context and task related opinions were recorded in an open questionnaire.

[3] Midas touch is an unintentional released input event, which is known in HCI from gaze interaction and named the Midas touch problem.

In the end of the first session, the initial gestures as well as the gestures the experts had proposed were evaluated but not the gestures proposed by the other experts. Thus, a second session was conducted in which the experts rated also the gestures that the other experts had proposed for gathering four evaluation ratings per gesture, one from each expert.

3.3 Results

The result of the expert interviews was an evaluated gesture vocabulary (Fig. 3.3), which contains feasible hand gestures that can be performed while grasping objects.

3.3.1 Q1: Gesture Repertoire

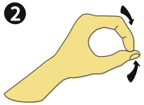
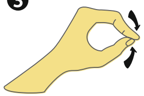
The final gesture set contained 21 expert evaluated finger gestures that are performable while grasping objects with all three main grasp types. 17 palm, 2 pad, and 2 side gestures were found (Fig. 3.3). Most gestures have several sub-types by performing them with different digits (index, middle, ring, and little finger, Fig. 3.3 (1)). Moreover, one gesture may allow for being performed differently, which leads to a completely new gesture. For example the gesture (1) of the repertoire in Fig. 3.3 could be performed as tap and as press gesture in dependence how much force is applied and how long the fingers are held in the final gesture pose. Furthermore, the gesture (6) in Fig. 3.3 could be performed as drag gesture and as swipe gesture, which would depend on the digit acceleration and motion duration.

Comparing the collected gestures with the established touch gestures for mobile devices shows a huge overlap. Almost all gestures (except Fig. 3.3, left (4), (10), and (12)) are combinations of tap, press, and drag gestures that can be found in user experience guidelines for touchscreens (Apple Inc. 2013). The exceptions (4), (10), and (12) rather rely on motions or poses, such as ‘flip’ (4), ‘scissor’ (10) or ‘okay’ (12).

3.3.2 Q2: Movability

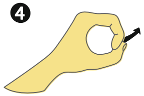
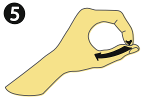
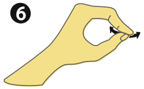
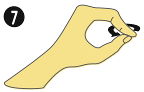
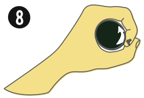
The results of the different evaluations were very similar over all experts regarding the movability, limitations, and the risk to perform a gesture accidently (Midas touch problem). This allowed for comparing the results and formulating general findings shown in Table 3.2. If the rating about the movability of a gesture varied, the more negative has been chosen in order to exclude the less feasible gestures from further examination, and to make sure that the gesture repertoire will work for a large number of users.

Table 3.2 Evaluation of the gesture repertoire that allows for being performed while grasping using the three main grasp types: palm, side, and pad

Fingermotions (while keeping the 3 grasp types)	Gestures (that are variations of the motion)	Description	Movability ratings per digit (scale pos. to neg.: ++, +, –, – –)	Limitations	Risk to accidently perform a gesture (Midas touch)
PALM 					
❶ 	Tap	Very short touching and immediate releasing the thumb tip at any finger nail while the thumb and the finger surround the held object	Index (I): ++	By relation of finger length and object diameter, i.e. steering wheel	High
			Middle (M):		
			Ring (R): +		
			Little (L): – –		
	Press	Holding a touch (0.5–1.0 s) with applied force at any finger nail with the thumb tip			
❷ 	Tap	Short touching and immediate releasing the thumb tip at any finger nail, while thumb and finger surround the held object	I: +	Large object diameter	High
			M: +		
			R: +		
			L: –		
	Press	Holding a touch (0.5–1.0 s) with applied force at the thumb tip with any finger			
❸ 	Tap	Very short touching with the thumb tip with any fingertip while thumb and finger surround the held object; and immediately releasing the touch	I: –	Large object diameter	High
			M: +		
			R: +		
			L: –		
	Pinch	Touching for about 1 s with applied force at the thumb tip with any finger tip			

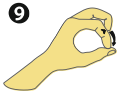
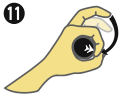
(continued)

Table 3.2 (continued)

Fingermotions (while keeping the 3 grasp types)	Gestures (that are variations of the motion)	Description	Movability ratings per digit (scale pos. to neg.: ++, +, –, – –)	Limitations	Risk to accidently perform a gesture (Midas touch)
❹ 	Flip	Flipping a finger apart from the thumb	I: + M: + R: + L: –	Large object diameter	Low
❺ 	Drag	Dragging with the finger along the inner thumb	I: + M: + R: – L: –	Just partly possible (close to the thumb tip) because of object diameter	Medium
❻ 	Ream	Reaming the thumb tip against a finger tip	I: + M: + R: + L: –	Hold object diameter (especially for little finger)	Low
❼ 	Circle	Circling the thumb tip around a finger tip	I: + M: + R: + L: –	Object diameter	Low
❽ 	Drag	Drag a finger across the surface of the object	All: –	General ability to flex finger while grasping is low	Medium

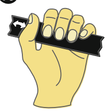
(continued)

Table 3.2 (continued)

Fingermotions (while keeping the 3 grasp types)	Gestures (that are variations of the motion)	Description	Movability ratings per digit (scale pos. to neg.: ++, +, –, – –)	Limitations	Risk to accidently perform a gesture (Midas touch)
❾ 	Drag	Drag a finger along another finger's back	All: –	General ability to drag a finger above another is low	Low
❿ 	Snip	In- and decreasing the distance between the stretched index and middle finger	+		Low
⓫ 	Tap	Tapping the object	Thumb (Th): – I: + M: + R: + L: +		Low
⓬ 	Thumb up	Stretching the thumb	Th: ++		Low
⓭ 	Drag	Dragging with the thumb along the finger nails	I: + M: + R: + L: –	Object diameter	Low

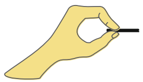
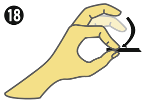
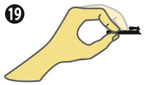
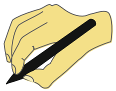
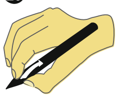
(continued)

Table 3.2 (continued)

Fingermotions (while keeping the 3 grasp types)	Gestures (that are variations of the motion)	Description	Movability ratings per digit (scale pos. to neg.: ++, +, –, – –)	Limitations	Risk to accidently perform a gesture (Midas touch)
14 	Drag	Dragging the thumb along the side of the index finger	Just partly possible because of object diameter	Object diameter	Medium
15 	Circle	Circling clockwise and anti-clockwise with the thumb around the fingers	I: + M: + R: – I: –	Object diameter	Low
16 	Drag	Dragging with the thumb along the object	Th: ++		Low
17 	Drag	Dragging with the thumb around the object	Th: –		Low

(continued)

Table 3.2 (continued)

Fingermotions (while keeping the 3 grasp types)	Gestures (that are variations of the motion)	Description	Movability ratings per digit (scale pos. to neg.: ++, +, –, – –)	Limitations	Risk to accidently perform a gesture (Midas touch)
SIDE 					
⓲ 	Tap	Tap a finger at the card	I: + M: + R:– L: –		Low
⓳ 	Drag	Drag a finger along the card	I: + M: + R: – I: –		Low
PAD 					
⓴ 	Tap	(I) Tapping on the stylus while writing	(I): –		Low
		(II) Tapping at the stylus while interrupt writing	(II): ++		
㉑ 	Drag	(I) Dragging a finger along the stylus while writing	(I): –		Low
		(II) Dragging a finger along the stylus while interrupting to write	(II): ++		

3.3.3 Q2: Limitations

Some gestures need more explanation as the movability of the required motions is not the same for all digits or any grasped object (Table 3.2). Movability may be limited in dependence on the physical objects that are grasped, for example, the size of the diameter of a steering wheel. On the other hand, movability can be limited by biomechanics, for example, it is difficult to move the ring finger without slightly moving the neighbor fingers as well, which was mentioned by the experts and goes in line with the literature (Cobos et al. 2007). Three parameters, the *form factor*, the *digit dependent limitations*, and the *grasp stiffness* are explained here in greater detail:

(1) *Form factor dependent limitations.* Especially the steering wheel gestures that require to surround the wheel with the hand and to reach the fingers with the thumb (Fig. 3.3 right, (1–7, 13–15)) depend on the finger length as well as on the wheel diameter. As shown in Fig. 3.4, the thumb can tap easily at the middle (b) and the ring finger (c) while holding the steering wheel; but depending on the wheel diameter tapping the thumb with the little finger (d) or sometimes also with the index finger (a) can be difficult, especially for people with small hands.

(2) *Digit dependent limitation.* The movability of the single fingers varies a lot because the middle and the ring finger are stronger connected through joint tendons and thus, these fingers harder to flex independently (Spalteholz and Spanner 1960). All experts were sure that the majority of users will be able to perform a separated index-finger tap without any problems. Also, moving the little finger separately from the others was rated as being not a problem at all. The separate flexibility of the middle finger is much worse than of the index finger. It is still feasible; but users might feel less confident. The range of finger inflexibility varies individually; but the ring finger is considered to be the least flexible for all users, followed by the middle finger while the index finger can usually be moved much better (Fig. 3.5d versus Fig. 3.5b, c). However, the little finger is also easily flexible (Fig. 3.5a); it has been indicated to not be very useful for grasp-based gestures as described above. The abandoned thumb works best and in comparison to all other fingers, even for sideways movements. That goes in line with the degrees of freedom of the

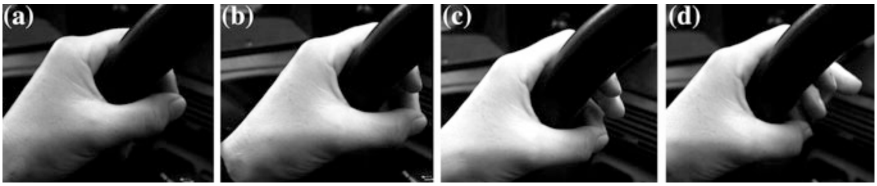


Fig. 3.4 Gesture movability depends on the relation between finger length and diameter of the steering wheel

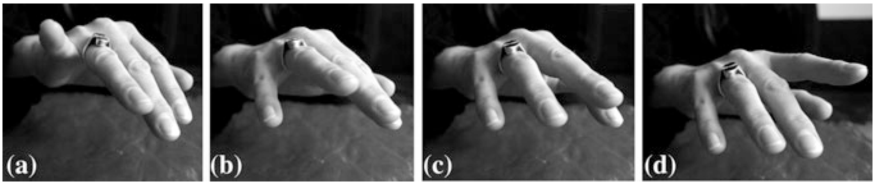


Fig. 3.5 Ability to stretch the little (**a**), ring (**b**), middle (**c**), and index finger (**d**) separately differs a lot and the ring finger can cause co-movements of the middle and of the ring finger

bottom joint of the thumb as shown in Fig. 3.1a and as explained by Cobos et al. (2007). These findings prove the assumption made in Table 3.1 based on available manual resources and inter-finger dependencies.

(3) *Grasp stiffness.* A grasp can be rather loose or stiff. The car scenario allows for the greatest number of gestures executed while steering a car. This is because the steering wheel is installed in the car, which allows for losing the grasp while executing a gesture. The other two scenarios require "carrying" the object. Here, losing the grasp for gesture execution is not appropriate. Thus, if the grasped object is carried, such as mobile devices mainly are, only few gestures, namely tap (gesture 18 and 20 in Table 3.2), drag (gesture 19 and 21 in Table 3.2) and variations of them (e.g. tap, press, and swipe), are executable without risking that the object falls down.

3.3.4 *Q3: Midas Touch Problem*

During the interviews, the experts were asked to rate the risk that a gesture would be performed accidently for each gesture (Table 3.2). The most simple and thus best feasible gesture, tap and drag, also often contain the risk to be executed without intention. Explanations when a tap may be a natural movement are given as follows: One expert mentioned that tapping the steering wheel while driving a car (Fig. 3.3, right, (11)) is a common behavior while waiting at the crossroads or listening to music. Some gestures might be performed in other situations, but for the ones the experts evaluated; they seemed to be quite unused in the interview scenarios. For instance, sliding the thumb against the index finger (Fig. 3.3, right, (6)) would be expected while cooking for adding salt to food, but while driving the risk of this slide-gesture occurring as a randomly executed natural movement is expected to be low.

3.3.5 Q3: Context

Verbal comments of the experts on the idea of allowing gesture-based interactions alongside a continuous grasping task were in general positive, while the opinion about the benefit of performing two tasks in parallel was different from one task to another.

All experts agree that there is a huge benefit in being able to control automotive applications while driving a car for safety concerns (steering wheel releases could be reduced). The experts agreed that the driving task is the most suitable for performing gestures because it is an automated and (compared to drawing and inserting a cash card into an ATM) rather a low precision task. That lower requirement on precision allows for finger releases without decreasing task performance. Thus, the experts had indicated a relatively high number of gestures that can be executed while grasping a steering wheel. An additional and essential reason for the appropriateness of executing gestures while holding a steering wheel is that the grasp is loose and does not need to hold the weight of the steering wheel. Thus, not only the grasp type influences the ability to move fingers while grasping but also the amount of force required to grasp an object. However, buttons embedded in steering wheels are already built in some cars; enabling gesture detection all over a steering wheel would allow for automotive controlling without readjusting the hand holding the steering wheel to reach a button.

However, the experts doubted performing hand gestures while inserting a cash card into an ATM is feasible because the short task duration, gesture execution before or afterwards the procedure of inserting an ATM card was not seen as a problem. That may be beneficial to replace entering a PIN with a number pad, which is commonly done sequentially with entering the card.

The last scenario concerned using a digital stylus, e.g. for drawing on a graphics tablet. Three of the experts thought that the possibility of changing the stroke width or the color while drawing would have a bad effect on the precision of the primary task; but all of them said that having these options during short interruptions could benefit the drawing task (and has been done by Song et al. 2011). The flow of drawing would be less disruptive and therefore the task could be completed more efficiently than if color selection would were to be done by keyboard or button-selection.

3.4 Discussion and Design Guidelines

Here the results are discussed and design guidelines for grasp-based interaction with a focus on ergonomics are described.

3.4.1 Context

The appropriateness of a context for grasp-based interactions depends on the following aspects that influence each other: the grasped *object* and the *task*.

(1) *Object.* The object influences the way to grasp it by its form factor as well as through the intended use (Wimmer 2011). Furthermore, the grasp affects the possibility to perform gestures while grasping as the grasp requires a certain hand pose and applied force per digit. The required force is a lot influenced by the object's weight. As an object with a certain form factor and weight requires to be held in a certain way; the grasp changes completely as a function of the force applied per digit if the object is installed in the environment, e.g. a steering wheel in a car. As less manual resources are involved in grasping, more resources are available to perform gestures. Thus, to perform gestures while grasping a steering wheel was rated to be the most appropriate context for grasp-based interactions, while holding the object with one hand (like a stylus or a cash card) limits the ability to execute gestures a lot. Therefore, objects that are held with two hands, such as tablet devices, are also promising to allow the user to execute gestures while grasping. That would allow one hand to lose the grasp for gesture execution, while the other is still holding the device stable.

(2) *Task.* Parameters that are given by the related task can decrease the possibility to execute gestures while grasping. Tasks may be too short and not allow the user to execute a gesture. Moreover, the task may require too much cognitive load for allowing interacting in parallel (e.g. target acquisition when inserting an ATM card). That decreases the ability to perform gestures at the same time. On the other hand, a task that lasts long and requires (occasionally) less precision, like steering a car, is most appropriate for performing gestures in parallel. Again, the usage of tablet devices fits to that need as holding a tablet requires almost no precision and takes as long as desired. If the device is held with two hands, one can easily occasionally release a digit and execute a gesture while the other is mainly holding the device.

3.4.2 Gesture Interaction

The choice of a gestural interaction design while grasping includes the *gesture type*, the *digit* that performs the gesture as well as the *location* the gesture is performed, such as free (in mid-air), on the user's body or on the surface of the grasped object.

(1) *Gesture type*. Two gestures types could be identified that fit for grasp-based interaction with every of the tested props, which are tap-based (Table 3.2, gesture (1), (2), (3), (11), (18), (20)) and drag-based (Table 3.2, gesture (5–9), (11–17), (19), (21)) gestures. In dependence on the grasp and the form factor of the grasped object, the gestures varied in order to the duration (e.g. tap versus press), to the detailed motions (e.g. circle drag versus straight drag), to the digits that performed the gesture, and to the location in which the gesture was performed (e.g. on-body versus on the object). The last two aspects are described below (see (2), (3) of this section).

However, the most generic gesture types are tap- and drag-based and even though they are extremely easy to perform and already are part of most natural movements; in designing for tap- and drag-based interaction the problem that the gesture may be executed accidently has to be considered. Solutions to solve this problem are choosing gestures that are unlikely executed in the task context (e.g. the ream gesture while driving, Fig. 3.3, right, (6)) or using clutch events in the interaction design that help the system to distinguish whether a movement was an intended gesture commend or a natural motion.

Many gestures were performed on the surface of the grasped object or on the body. That suite well with established gestures, such as tap, drag, press, release, and swipe, which are commonly implemented in mobile devices, such as phones and tablets. Thus, the experts may be inspired by known gestures, which in the end would ensure that the gesture vocabulary needs no training and is easy to learn. However, most common gestures have an analogue counterpart in the presented gesture vocabulary; the established pinch gesture executed through two digits on the same surface, which is usually used for zooming on touchscreens, is not part of the gesture vocabulary. Pinch on a 2D surface with two digits of the same hand that is holding the device is not ergonomic as that gesture is only performable if the hand releases completely the grasp; and thus, pinch is not part of the ergonomic grasp-based gesture vocabulary. Instead, pinching two fingers against each other is feasible while loosely grasping a steering wheel, as here the applied forces support the grasp. For a two-handed grasp, the pinch gesture could also be executed on the same device side but with two hands.

Some tap- or drag-based gesture performances depend on the form factor of the grasped object. For example, a tap between the thumb and a finger around a steering wheel may be difficult when the diameter is too large. Thus, any gesture execution that requires surrounding the object with the hand depends on the relationship between the diameter and form factor of the object held in hand and the length of the digits.

(2) *Digit*. Beside the finger length that may cause problems of gesture execution; the digits differ also in movability. The thumb has the most degrees of freedom and is best flexible (if not necessarily required for grasping). The index and the middle finger were also rated to be well feasible while grasping. The ring finger is not recommended as it results in co-motions of the neighbour fingers; and the little finger was also rated to not perform very well, especially due to its length.

(3) *Location*. Free/mid-air gesture performance while grasping (Table 3.2, gesture (10) and (12)) is only possible if the grasped object is fixed in the environment like a steering wheel. That is also the case for on-body gestures (Table 3.2, gesture (1–7), (9), (13–15)) as for them the grasp has to be very loose. Thus, tap- and drag-based gestures executed on the grasped object are the most generic gestures as they are executable during all grasp types, and they also refer to established tap-based gestures, such as tap, drag, and swipe and thus, may be easily learnt.

3.5 Conclusion and Contribution

3.5.1 Conclusion

In the expert interviews explained in this chapter, touch-based gestures, in particular tap, drag, and modifications of both, were identified to be best feasible while holding objects with any of the three main grasp types; and thus they are promising for further research on grasp-based interaction with tablet devices. That includes interactions at the front as well as at the back of a tablet when holding it with both hands as the thumb as well as the index and the middle finger can easily execute gestures while holding the device. The ring finger may be less flexible; and the little finger may be too short for being appropriate to execute tap gestures while holding tablets.

Although, tap and drag gestures may seem to be enough for interacting with a mobile device; variations of them cover also swipe gestures, hold-overs or press gestures, tap, double tap and so on. Thus, the common touch gesture vocabulary is well executable while grasping a tablet; except the pinch gesture if both digit of one hand are touching the same surface cannot be recommended to be an ergonomic gesture for the presented device hold.

3.5.2 Contribution

This chapter provides the following contribution:

- A gesture repertoire is defined by experts, which contains gestures that are feasible while objects are held with the three main grasps.
- The gestures of the repertoire are evaluated according the flexibility for each digit, ergonomic limitations of gesture execution, and the risk a gesture causes the Midas touch problem.
- Guidelines are provided that propose suitable tasks for grasp-based interactions as well as the selection of appropriate gestures.
- Parts of this chapter are published in Wolf et al. (2011b) as well as discussed in Wolf (2011, 2012).

Chapter 4
Ergonomic Characteristics of Grasp-Based Touch Gestures Executed on Two Tablet Sides

Gestural interaction is implemented in almost every mobile device and there are established gesture detection libraries for Android, iOS, and mobile browsers. Their gesture detection thresholds slightly differ for gesture detection on phones versus on tablet devices. Thresholds for back-of-device gesture detection do not exist.

This chapter investigates how gestures are executed at different surface areas of tablet devices while holding it with both hands. Thereby the gestures defined to be most promising for grasp-based interaction in Chap. 3 will be used for this exploration.

The varying flexibility of the different digits that was identified in Chap. 3 is motivating this exploration. While holding a tablet with a symmetric bimanual grip, the thumbs can execute touch gestures on the front side and the fingers can reach the back of the device. If the digits, especially the thumb and the fingers differ significantly in flexibility and movability, gestures on the back of tablets would be performed differently than on the front side. If that is true different thresholds for detecting gesture on the front and on the back of bimanually held tablets are needed.

Thus, this chapter focusses on gesture execution depending on the used digit. The aim is to identify ergonomic parameters for gesture detection on both, the front and the back of a bimanually held tablet.

This exploration contributes through showing that the gesture execution slightly differs between both devices sides. Thresholds for detecting gestures on both sides of bimanually held tablets are provided. Moreover, the idea to use two parameters: touch duration and path length for identifying Midas touch events is introduced. These results lead to design guidelines, which allow for ergonomic gesture design and implementation based on empirical research.

4.1 Device-Side Dependent Gesture Execution

Here, an observational study is chosen as method to explore how ergonomic gestures should look like. Participants are asked to execute touch-based gestures (tap, press, drag, and swipe) with the aim to explore their position, length, shape,

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DOI 10.1007/978-3-319-13981-4_4

and duration. The tap and drag gestures were chosen because they were found in Chap. 3 to be easily feasible while grasping (Wolf et al. 2011b). The press and swipe gestures also are considered as they are very similar to tap and drag. Thus, it is expected that these gestures are also ergonomic and easily feasible while grasping. Moreover, all four gestures are common Android gesture patterns (Android Developers Design Patterns 2013). An investigation on gesture parameters for tap and press aims furthermore to serve for distinguishing unintentional touches from intended gestures.

As widgets are commonly orientated horizontally or vertically, the experiment presented here investigates drag and swipe, when executed in horizontal and vertical directions. Due to the scope of this thesis, all gestures are explored when they are performed on the front and the back of a tablet.

4.2 Method

To gain insight about how users prototypically execute tap, press, drag, and swipe gestures in horizontal and vertical orientation on the front and the back of a grasped tablet, participants were asked to execute these gestures while their activities were recorded.

4.2.1 Design

An observation was designed where 18 participants, 7 female and 11 male, aged between 23 and 37 years (mean = 28, SD = 3) volunteered.

A $6 \times 5 \times 2 \times 2$ within design with repeated measurements was used. The dependent variables were gesture (tap, press, horizontal drag, vertical drag, horizontal swipe, and vertical swipe), digit, hand, and device side. The independent variables were x-positions and y-positions of the changing touch points while the gestures were executed for later analysis of the gestures paths.

4.2.2 Task

The participants were asked to execute tap, press, drag, and swipe gestures with both hands and each digit per hand. The drag and swipe gesture were executed in the horizontal as well as in the vertical direction. All combinations were executed separately on the front and the back of the device five times each while holding the device with two hands in a standing position.

4.2.3 Apparatus

An ASUS Eee Pad Transformer TF101 was used as interactive prototype. An application was developed for recording the touch events with no visible display. For recording the touch events of the fingers at the back of the device, which has no capacitive surface; the device was flipped so that the back side was facing the users. For recording the touch events of the thumb, the device was held in the standard position.

4.2.4 Measurements

The touch events on the tablet were recorded in log files for 18 participants and contained five trials per device side, hand and digit for four gestures, 2 gesture orientations (horizontal, vertical) for swipe and drag; 10,800 in total. Moreover, handedness and demographic data were recorded by a questionnaire.

4.2.5 Procedure

Eighteen persons participated in the experiment. After an introduction, they solved the gesture execution task five times with each finger per hand. Half of the participants started with their dominant, the other half with their non-dominant hand in a standing position. After completing the tasks, the participants filled in a questionnaire.

4.3 Results

For each gesture, *typical gesture parameters,* such as touch position, path length, and execution time were identified, which later on will be discussed regarding their potential to serve for design and implementation guidelines. For each parameter it was tested whether they are independent from the gesture orientation or if they depend on the side they were executed (front versus back of tablets) as well as whether they have been executed with the dominant or non-dominant hand.

The individual vectors for each gesture *tap, press, drag*, and *swipe*, and typical gesture vectors using the median (Table 4.1) are drawn (in orange and in black) to scale of a tablet screen of 1,280 × 742 pixels in Fig. 4.1. The individual gesture

Table 4.1 Typical gestures: medians for path length (Fig. 4.1), gesture duration, and velocity on both device sides, both gesture orientations and with both hands

Gesture	Device side	Path length px (mm)		Duration (s)		Velocity px/s	
		Left	Right	Left	Right	Left	Right
Tap	Front	1	1	0.2	0.2	5	5
	Back	4	8	0.2	0.2	20	40
Press	Front	4	7	0.7	0.7	6	10
	Back	17	18	0.7	0.7	24	26
Drag vertical	Front	314 (48)	291 (45)	1.0	1.1	249	251
	Back	213 (32)	183 (28)	0.9	0.7	2,586	2,569
Drag horizontal	Front	247 (38)	221 (34)	0.8	0.7	216	233
	Back	206 (32)	193 (30)	0.9	0.7	2,632	2,560
Swipe vertical	Front	265 (41)	285 (44)	0.3	0.2	10,757	10,689
	Back	196 (30)	203 (31)	0.3	0.3	2,926	2,617
Swipe horizontal	Front	212 (32)	214 (33)	0.2	0.2	12,188	15,678
	Back	189 (29)	174 (27)	0.3	0.2	3,211	2,700

vectors differ a lot, which is shown by the widespread location of the whole set of gesture vectors that are drawn in gray. The large variety in gesture placement for the participants is also represented through the large standard deviations for the gesture means (Fig. 4.2). Here, the vector means of all gestures (tap, press, drag, and swipe) are presented.

4.3.1 Gesture Position

Regarding the gesture positions, the median values for tap and press gestures were always located close to the vertical edges where that hands are places. The gesture positions differ a lot in their vertical position but less horizontally. The touch positions of the gestures when executed on the front are again slightly closer to the edge/hand palm than those performed at the back of the device.

4.3.2 Gesture Shape

Different gesture shapes for drag and swipe gestures were observed. The vectors for horizontal gestures are slightly tilted upwards towards the middle of the screen, comparable to a fishbone pattern. Vertical gesture paths are drawn like a bow, and the imaginary middle of the circle would be inside the palm (Figs. 4.1 and 4.2).

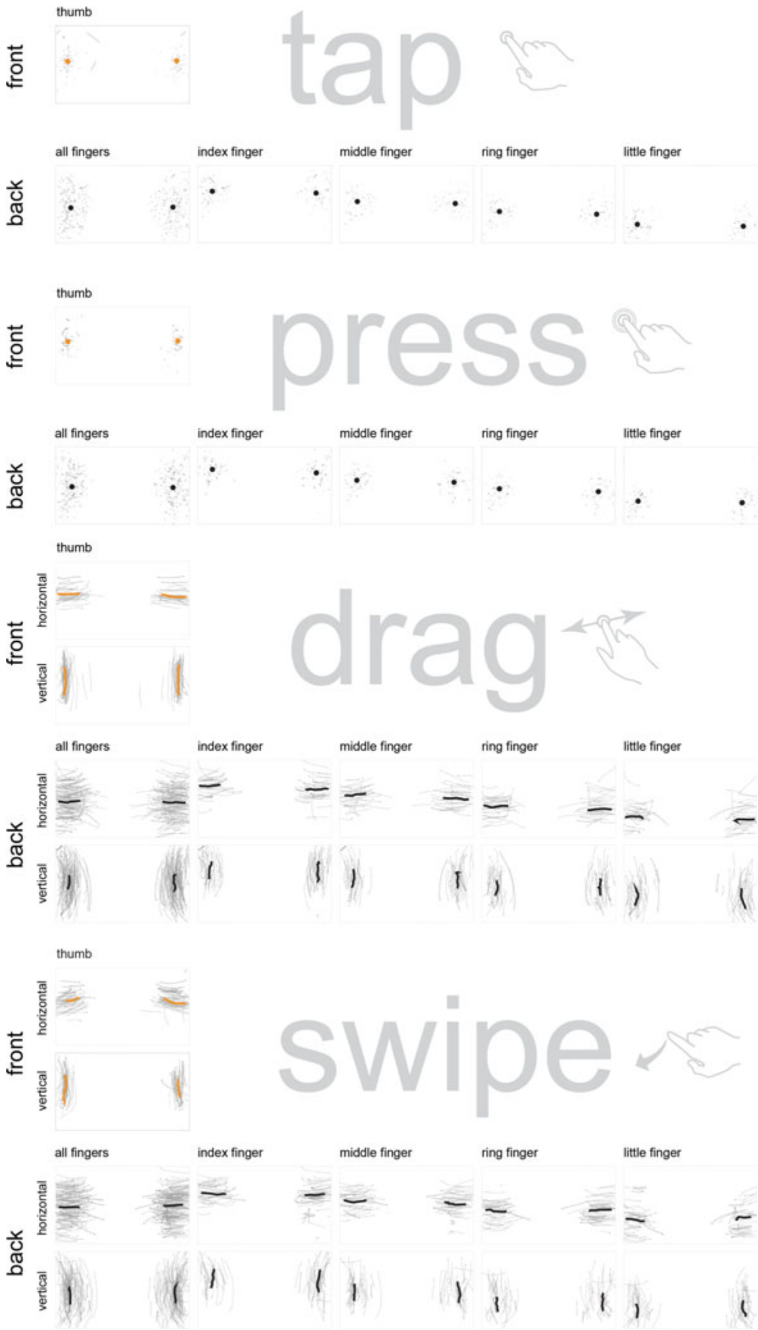

Fig. 4.1 Gesture vectors (*grey*) and median for *front* (*orange*) and *back* (*black*, see-through view) of a tablet, drawn to scale of a tablet screen of 1,280 × 742 pixels

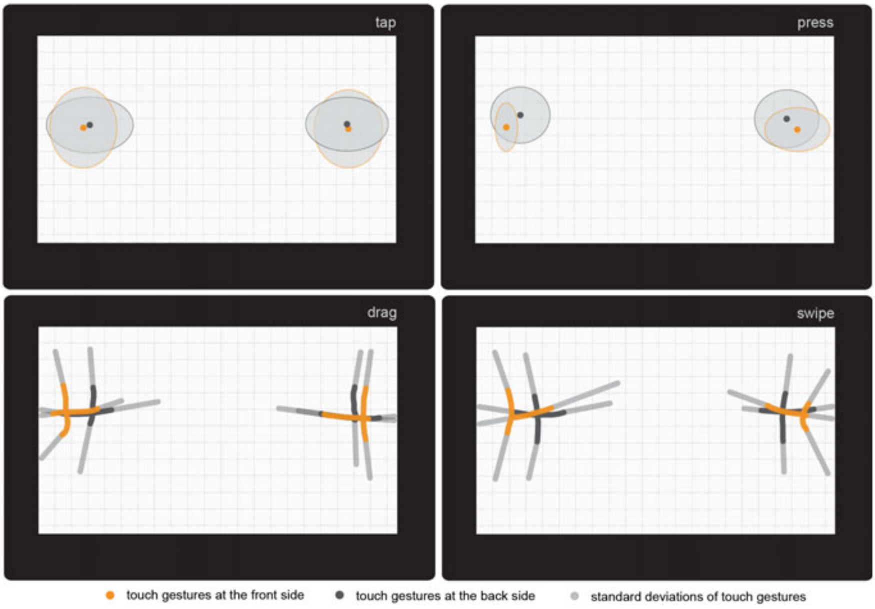

Fig. 4.2 Vector means per gesture (*red* for thumb and *blue* for index and middle fingers on the back in see-through view) and SD (*grey*) drawn to scale of a tablet screen

4.3.3 Gesture Orientation

The gesture path *orientations* (horizontal, vertical) did not affect direction-independent vector parameters (gesture path length: $F_{1,953} = 2.379$, $p = 0.123$, gesture execution duration: $F_{1,1623} = 1.545$, $p = 0.214$) in an ANOVA.

4.3.4 Hand Symmetry

The gesture execution is symmetric for both *hands* as shown in Figs. 4.1 and 4.2. This means that the gesture vectors are flipped on an imaginary vertical line drawn in the middle of the screen. Thus, the positions (considering that they are vertically flipped) are not affected ($p = 0.929$), and the drag as well as swipe paths do not differ in length regardless of whether they have been executed with left or right hand ($p = 0.885$).

While the gesture vectors look similar for the right or left hand, gesture execution duration differs significantly for both *hands*. Moreover, a significant interaction effect between *hand* and *gesture* was found for execution duration ($p = 0.003$).

How the four *gestures* were executed differently in regards to duration and vectors will be explained in the following section.

4.3.5 Front-Versus Back-of-Device

The gestures differ in path length if they were executed on the front versus on the back of tablet ($p < 0.001$). Moreover, Fig. 4.3 visualizes that the gesture vectors of drag and swipe are significantly longer than tap and press, which by definition are close to

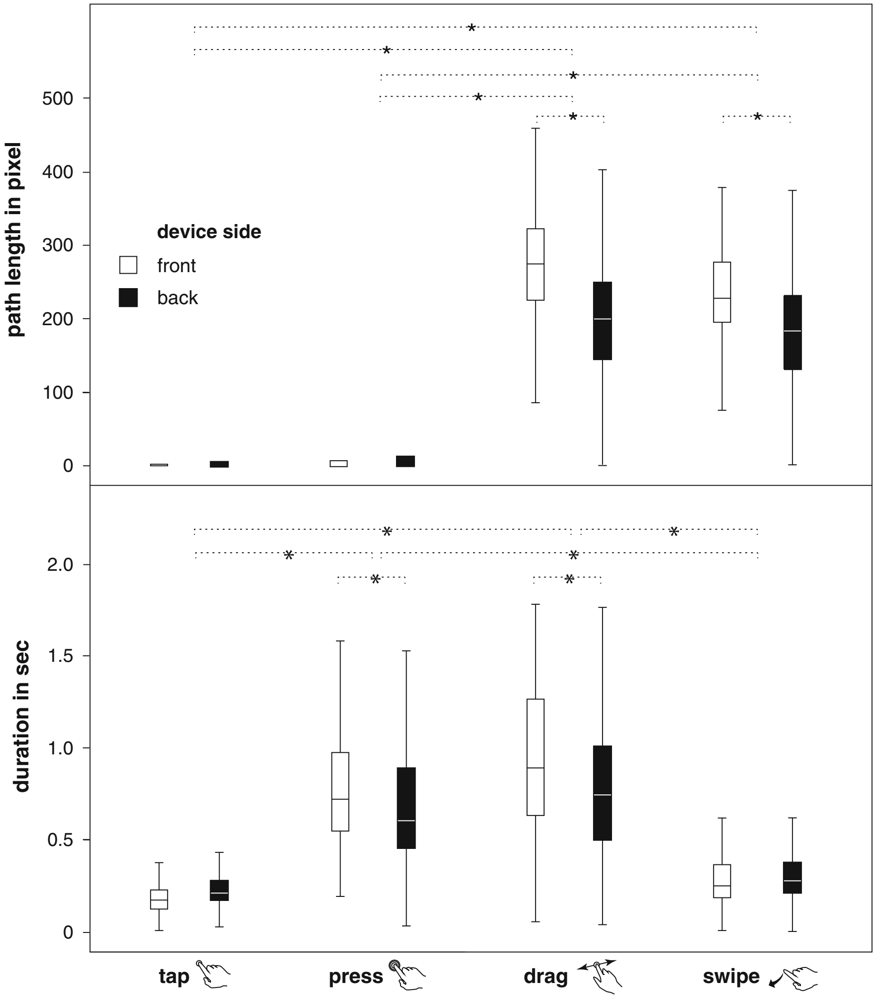

Fig. 4.3 Boxplot of path length and duration for each gesture and significant differences* in between

zero. Swipe and tap are faster than drag and press ($p < 0.001$). Their values are almost independent and can therefore serve as gesture classification as it is already the case in common touch gesture APIs like for iOS, Android, and mobile browsers. Interestingly, the duration and path length sometimes vary for the same gesture when executed on different device sides: drag and press are slightly, but significantly longer on the front side where the gestures are performed with the thumb. Furthermore the vectors for drag and swipe are a significantly longer when performed with the thumb on the front of the tablet compared to the gesture paths on the back side. This is indicated as an interaction effect between *gesture*device side* (Fig. 4.3) and swipe on the back of the device has much less velocity ($p < 0.001$) than on the front.

4.4 Discussion

Analysis of the gesture data gained insights into positions of gesture execution as well as into gestures paths.

The gestures were executed close to the positions where the hands were grasping the device. These positions are in line with the interaction areas for bimanual held tablets defined for touchscreens by Odell and Chandrasekaran (2012).

The parameters of the gesture paths are significantly influenced by the gesture type and the device side. The used hand influenced execution time but not the paths. The gesture orientation was neither affecting execution time nor path. On mobile devices, gesture recognition thresholds are defined by these parameters. The results of the presented observation are an argument to define different recognition threshold for gestures performed on the touchscreen versus on the back of a tablet.

For comparing the presented parameters with established gesture recognition parameters for mobile devices, first recognition thresholds used for Android devices, in mobile browsers (JavaScript), and from related work are presented. Then their values are compared with the observed parameters. Afterwards, specific design guidelines for bimanual interaction with tablets are provided, especially for gesture detection distinguishing between touchscreen and back-of-device interaction with bimanually held tablets.

4.4.1 Common Gesture Parameters

In common Android APIs for mobile devices, touch durations, path length per second, and velocity of the touch motion serve for gesture detection. For instance, a press (also named taphold) is fired when a touch lasts longer than 0.5 s for Android applications. This threshold is accessible with the getLongPressTimeout command and applies to Android phones, such as Galaxy S I9100, Galaxy S3 I9300, and Google Nexus S with Android 4.1.2, as well as for the tablet Asus EeePad Transformer TF101 (Android Developers Reference 2013). The press/taphold threshold for common mobile browsers is 0.75 s (JavaScript API jQuery 2013). A touch gesture of shorter duration is defined as tap. Moreover, for common mobile browsers, a swipe is defined to be a special drag that is at least 30 pixels but not more than 75 pixels (11 mm) long and also is executed within one second. In Android, a swipe is defined through velocity (pixels per second). The velocity threshold of swipe, which does not serve for gesture detection but as a base map for velocity on scroll friction, this is defined for most Android phones (Galaxy S I9100 and Google Nexus S with Android 4.1.2) to be within a range from 75 to 12,000 pixels per second or between 50 and 8,000 pixels per seconds for an Android tablet device, such as the Asus EeePad Transformer TF101. These touch gestures were defined for front-of-device touch gestures. A prototypical drag path on the back of a mobile phone that is executed with the hand that holds the device is about 130 pixels or 20 mm (Wolf et al. 2012a).

4.4.2 Android Versus the Observed Parameters

In the following list, the findings of the presented observation are compared with the thresholds for gesture detection in common mobile Android devices:

1. The detection of tap and press is roughly consistent for all mobile devices, and the presented results are in line with the established thresholds for the front and also the back of a tablet.
2. The detected durations of tap (0.2 s) and press (0.7 s) for both, the front and the back of the device are in line with the Android thresholds (tap: <0.5 s, press: >0.5 s) (Table 4.1, Fig. 4.3).
3. A prototypical drag performed on a tablet is 30–50 mm, and thus 1.5–2.0 times longer than on the back of a phone (Wolf et al. 2012a).
4. The detected velocity for swiping on the frontscreen (avrg_front: vertical: 10,723, horizontal: 13,933; avrg_back: horizontal: 2,956, vertical: 2,772), which serves for mapping the swipe execution onto scroll friction, is within and for horizontal front swipe above the range of several Android phones (from 75 to 12,000 pixels per second) and for back-of-device within, but for touchscreen interaction above the range of the Android ASUS tablet (between 50 and 8,000 pixels per seconds). The values are rated above the common ranges as acceptable: users would just have no problems to scroll fast. If the maximum velocity cannot be reached, which is suggested for back-of-device interaction, the mapping should be defined correspondingly. As back-of-device swiping was up to four times smaller for back-of-tablet interactions compared to swipe velocity on the front, dividing scroll parameters by four for back-of-device interaction would be recommended.
5. No thresholds are defined in existing APIs for distinguishing an unintended touch event. That event would cause Midas touch problems in back-of-device interaction. According to the presented results, touch events on the back of

tablets that last longer than 1.0 s (considering 1 SD safety distance from the press/taphold mean) without moving are unintended touch events.

6. In summary, gesture on the front last longer (drag, press) and are drawn over a greater distance (drag, swipe) than gestures on the back of the device. A reason for this is probably that gestures on the front are executed with the thumb is more flexible than the fingers (Vardy 1998, Fig. 3.1).

4.4.3 Design Guidelines

Regarding touch gesture classification and design recommendation, the results of the presented observation can serve for concluding design guidelines. As shown in Fig. 4.4 and Table 4.1, the data of the presented observation contains distinguishable thresholds for gesture paths and durations, but also for Midas touch. Furthermore, the shapes and positions of the gestures gain insights that lead to recommendations for how to place and design widgets.

Recommended design guidelines for detecting touch gestures and for designing widgets are:

Touch Gestures

- *Tap*: triggers after releasing a quick touch event that due shorter than 0.5 s. The touch was not moved in any direction. But for allowing little accidental slips, a path threshold of 10 pixels (1.5 mm) is recommended.
- *Press/taphold*: triggers after releasing a touch event that lasts at least 0.5 s.
- *Midas touch*: is indicated if a touch event lasts longer than 1.5 s. (That is 2 SD or longer than the pressure/taphold mean, which is taken as safety space.)
- *Drag*: triggers when a touch is moved more than 10 pixels (1.5 mm) over a time of at least 0.6 s. Longer gesture durations are possible as drag is appropriate for position control that allows for directly manipulating a parameter as long as the touch is moving. A drag that is aimed to be drawn with one stroke without readjusting should not be longer than 320 pixels (49 mm) on the front and not longer than 250 pixels (38 mm) on the back side.
- *Swipe*: triggers when a touch is moved more than 10 pixels (1.5 mm) but faster than 0.5 s. The swipe is performed slower on the back that results in lower friction. Thus, mapping factors onto scroll friction have to be higher for back-of-device swipe gestures.

Widget Design

- *Buttons on the front and on the back*: should be placed near the vertical edge and in the upper horizontal middle. The area in distance to the vertical edges and in the center of the device should be avoided for placing buttons as reaching them requires to release a hand from the device. The results presented here are in line with the touchscreen interaction areas of tablets defined by Odell and Chandrasekaran (2012).

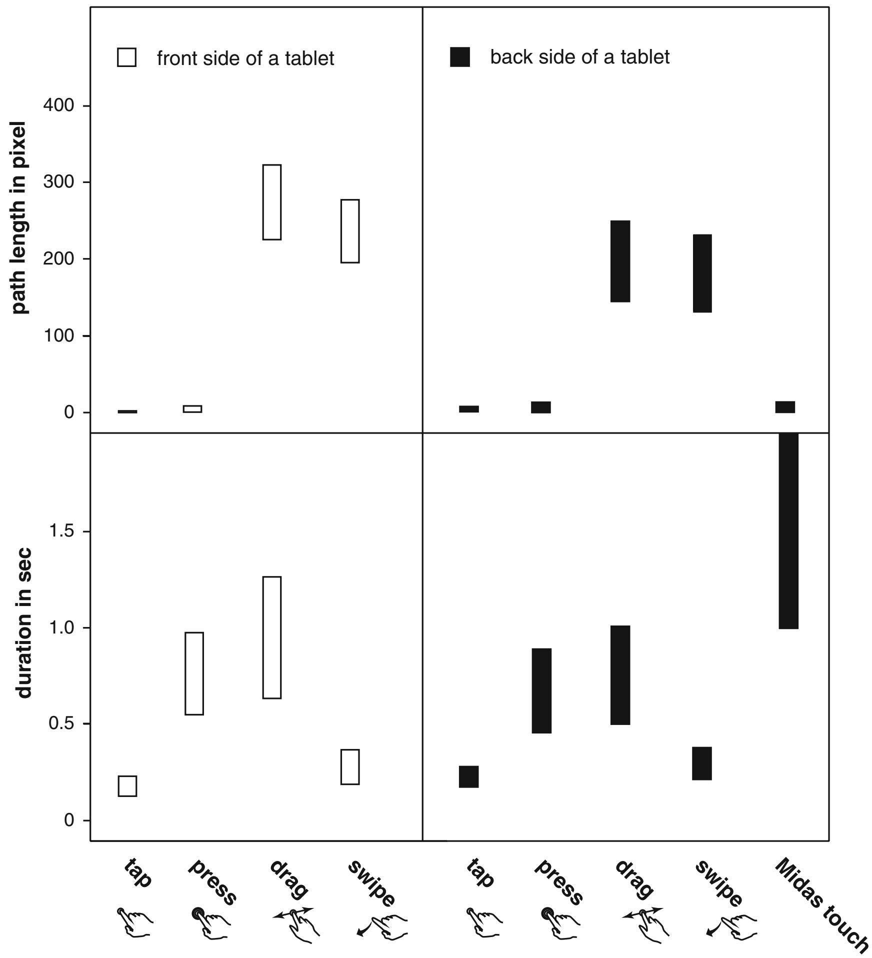

Fig. 4.4 The bars represent 50 % confidence of prototypical touch gesture paths and durations. Values that refer to a Midas touch event are proposed

- *Sliders on the front and the back*: Similar to buttons, sliders should be located close to the vertical frames for easy access. For vertical sliders a rather curved drag performance is suggested and therefore sliders might be shaped as bows with the imaginary center point in the palm of the tablet-holding hand. Sliders on the back side might be smaller sized than on the front for both: vertical (front: max. 290 pixels or 44 mm, back: max. 180 pixels or 28 mm) and horizontal orientation (front: max. 220 pixels or 34 mm, back: max. 190 pixels or 29 mm). Otherwise the user may not be able to drag above the whole slider with a single stroke and without releasing the touch.

4.5 Conclusion and Contribution

4.5.1 Conclusion

The presented observation was motivated by the belief that design guidelines for touchscreen interaction cannot automatically be adapted for back-of-device interaction. Furthermore, holding a tablet with both hands is easier; but gesture execution is limited while the device is held with both hands.

The intention of the work presented in this chapter is to establish guidelines, which are specifically developed for bimanual tablet interaction for touch gestures executed on touchscreens and on the back of the device.

An exploration was presented on how touch gestures prototypically look like if a tablet is held with two hands. Gestures were recorded and analyzed to gain insights into how prototypically executed gestures look like. Based on that data, design guidelines—similar to these, which are commonly described in developer APIs—were defined and rules for touch gesture classification were proposed for both tablet sides.

4.5.2 Contribution

This chapter provides the following contributions:

- Diagrams with typical gesture vectors for tap, press, drag and swipe gestures are provided for front- and back-of-device interaction when they are executed while grasping a tablet with a symmetric bimanual grip.
- Threshold for these gestures are presented for both device sides that can be used for gesture implementation.
- Thresholds are proposed to distinguish a Midas touch event from a touch gesture.
- Design guidelines are proposed to implement grasp-based gestures for front- and back-of-device interaction on a tablet with a symmetric bimanual grip
- The results of this chapter are submitted under Wolf et al. (2014a).

Chapter 5
Interaction Areas on the Front and on the Back of Tablets

This chapter aims investigating interaction areas regarding two aspects: at first interaction areas that have a high risk to trigger Midas touch events are explored; and then interaction areas that are in reach of direct touch are investigated.

To explore the Midas touch problem, an initial user observation study is explained that investigated areas that may be unintentionally touched while holding the device. Afterwards, accessible areas on the front and the back of tablets are explored. The findings of both studies are analyzed and distilled into guidelines for GUI layouts and appropriate widget positions.

5.1 Interaction Areas on Hand-Held Tablets

As the hand-held device—in this case a tablet—defines the gesture space for any grasp-based interaction, the need of understanding the grasp is mandatory. As stated in the related work, there are different ways to grasp a tablet. A stable and common grip is to rest the device on the fingers that touch the rear.

If both device sides are touch-sensitive, the risk increases that the fingers may touch a sensor while simply holding the device and unintentionally release a touch event. This type of unintentional input events are known in HCI from gaze interaction and named the Midas touch problem (Istance et al. 2008; Jacob 1990).

Trudeau et al. (2012) found for one-handed phone interaction that the thumb performs best when its pose is relaxed, neither strongly bent nor completely stretched. Thus, the thumb does not reach the entire interaction areas on mobile phones when using the hand that holds the device. That lack in accessibility of the interaction area increases dramatically for larger devices, such as tablets.

After introducing relevant measurements for tablet accessibility, two user studies are explained. In the first study, it is investigated which surface areas are unintentionally touched when a tablet is held (see Sect. 5.3). Afterwards, a second user study that investigated areas that can be intentionally reached with each finger on the rear and with the thumb on the front is presented (see Sect. 5.4).

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T-Labs Series in Telecommunication Services,
DOI 10.1007/978-3-319-13981-4_5

5.2 Ergonomic Measurements

If the tablet grasp is given, one may suggest that the area the digits can access can be calculated using the dimensions of the tablet and measurements of the hand. In the following sections these parameters are described for discussing the results in dependence of the ergonomic measurement afterwards.

5.2.1 Device

Two devices, an iPad2 and an ASUS Transformer are considered here. The iPad is sized 24.28 × 18.97 × 1.34 cm. The dimensions of the ASUS Eee Pad Transformer TF101 are 27.1 × 17.1 × 1.3 cm. Both device types have in common that their center is hardly accessible while the devices are held with a symmetrical bimanual grip in landscape format. The accessibility of the presented observations will be measured from the edges of the devices. Thus, the little difference in device size does not affect the comparability of the results.

5.2.2 Hand

The relevant hand parameters for accessing positions on grasped tablets are the palm length and the lengths of the digits. The percentiles of the parameters are presented Table 5.1 (after Lange and Windel 2006).

Table 5.1 Percentiles of palm and digit lengths for Germans in cm

	Percentiles					
	Female			Male		
Hand part	5 %	50 %	95 %	5 %	50 %	95 %
Palm	9.1	10.0	10.8	11.1	10.9	11.7
Thumb	5.2	6.0	6.9	6.0	6.7	7.6
Index finger	6.2	6.9	7.6	6.8	7.5	8.3
Middle finger	6.9	7.7	8.5	7.5	8.3	9.2
Ring finger	6.5	7.3	8.0	7.0	7.7	8.6
Little finger	5.2	5.8	6.6	5.6	6.2	7.0

5.3 Midas Touch Events on the Hand-Held Device

For several years now, researchers have recommended to use the back of a device for touch input (Wigdor et al. 2007; Baudisch and Chu 2009; Shen et al. 2009). Because the back side of a tablet is often touched for holding, an observation was conducted that questioned which areas were unintentionally touched while a tablet is held with both hands. The Midas touch problem was in Chap. 3 identified to be a design challenge for grasp-based interaction.

The observation presented here aims to investigate whether or not these areas are touched for grasping. That question will help finding insight in how to design touch-based interactions on the back-of-device of tablets that are held with two hands. The design challenge addressed here is the risk of unintentionally released commands that may occur when users hold the device.

5.3.1 *Method*

To answer the question of how users naturally grasp a tablet without paying attention, data of the touch events on the back of the device was collected while participants were not aware of the recordings.

5.3.1.1 Design

To collect unintended touch events the recording was done while users were listening to instructions during a typical HCI user study (see Wolf et al. 2012b for details). That experiment was designed for an explorative investigation on the natural way to grasp a tablet with two hands. Therefore, data from 10 right-handed participants, six female and four male, aged between 24 and 64 years (mean = 35.5, SD = 13) were collected. The chosen method is an explorative approach that aims to gain qualitative insight in touch behavior rather than providing data for quantitative analysis. The experimental situation when the participants are listening to instructions is suggested to be similar to non-interactive use cases, such as reading emails or watching videos.

5.3.1.2 Task

The participants were asked to hold the device (Fig. 5.1) while standing and listen to instructions of a task-driven user study. During that time the touch events of the rear touchscreen were recorded.

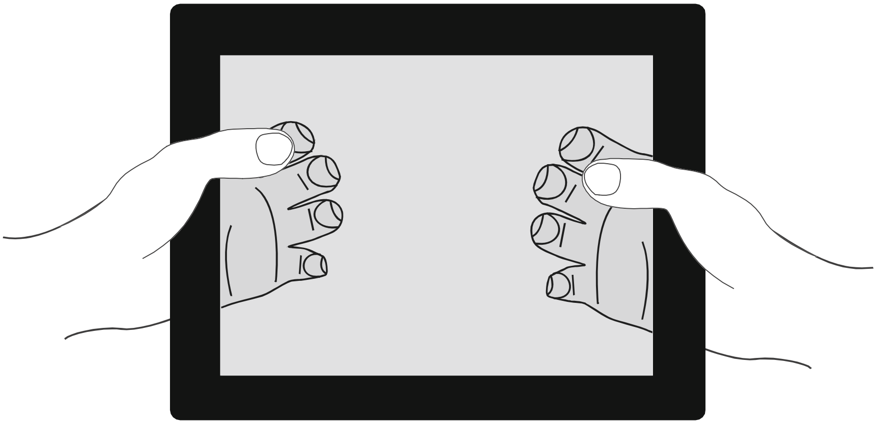

Fig. 5.1 Participants were holding the tablet without further instruction. The see-through visualization shows the fingers at the rear but was not implemented for the prototype

5.3.1.3 Apparatus

The interactive prototype consisted of two iPad devices glued together back-to-back to allow sensing thumb touch events at the front and on the rear (Fig. 5.1) that was inspired by Shen et al. (2009). Their weight was approximately 1200, 600 gm each. The weight of two devices will cause fatigue and may cause the need to readjust the grasp after a while. As the touch events collected in this observation study serve to show that grasping causes unintentional touch events on the back of the device, the weight of two devices does not limit the expressiveness of the results.

5.3.1.4 Measurements

The touch events of the front- and of the rear-sided iPad were recorded for exploring the way users grasp a device. Additionally video was recorded to record touch events on the bezels of the front and of the back of the device, which have no capacitive sensors.

5.3.1.5 Procedure

Participants were invited to volunteer in a HCI user study. The time participants listened to instructions between the first and the second task during the user study was chosen for collect data for this grasp exploration. The procedure of holding and waiting took about 2 min. The participants did not know that their touch events were recorded while listening to our explanations to make sure their grasp was natural. After the experiment, the participants were informed about the data collection, but they are also not to reveal this to other participants.

5.3.2 Results

The natural grasp was determined as the touch events during about 120 s when the participants were listening to instructions. At that time the participants held the device mainly without any grasp readjustments. Because of problems with one logfile, just results of nine participants were analyzed. The static back-of-device touch positions of all participants that were recorded were merged in one map (Fig. 5.2) for displaying the surface touch positions of each finger for all participants. Fingers that touched the bezel for holding the device are not represented in the data of Fig. 5.2. Thus, video recordings were analyzed (Figs. 5.3 and 5.4), which contained more information, e.g. the finger positions at the device bezel.

When the tablet was held with two hands without completing any task, the grasp was by nine out of ten participants configured using with the same fingers of both hands. Thus, the grip was symmetrical in terms of the used fingers. Two participants held the device without generating touch events on the rear touchscreen because they were grasping it through touching the bezel (Fig. 5.3). All touch events were produced through the participants' fingertips.

The majority of the participants held the device in an almost planar orientation (i.e. like a dinner tray) so that the device was resting on the finger tips (Figs. 5.2 and 5.3).

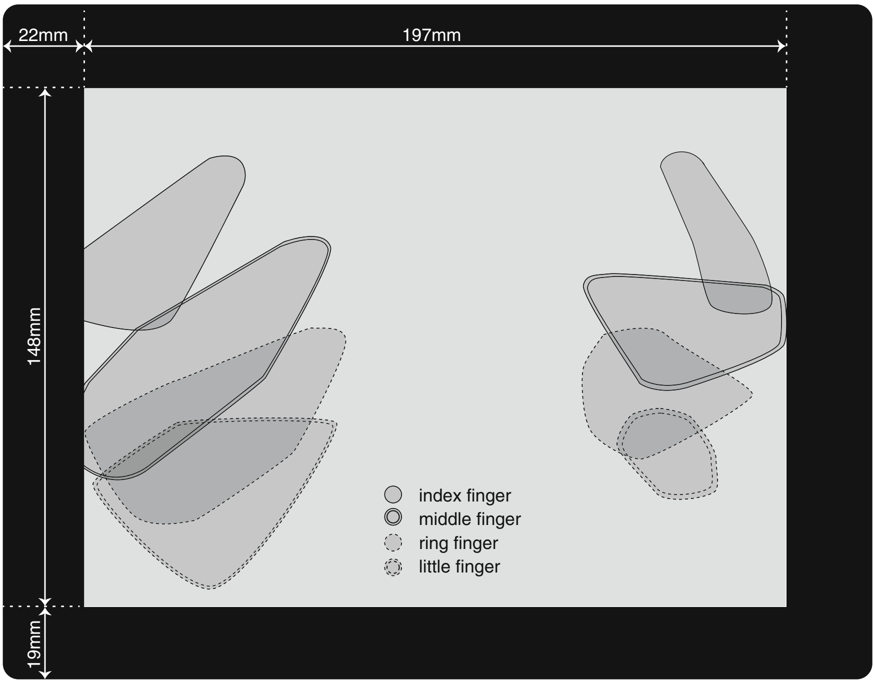

Fig. 5.2 Touch areas for the fingers on the back of the device. The rear touch events are shown from a see-through perspective. So the device is shown from its front

Fig. 5.3 Finger position on the back of the device while holding it

The palm often served as grasp support for holding the device. Only one participant touched the frontscreen with the thumbs; and the video data (Fig. 5.4) revealed that actually almost all participants (except one) supported the grasp through touching the front side of the bezel with their thumbs. One participant who did not touch the front side rested his thumbs on the device's side.

The results show that neither the fingers that touch the back of the device nor the fingers' position can be predicted. Of course, the fingers touched the surface in vertical order and in a certain distance from the vertical edges. The grasp adjustment was roughly given by the hand anatomy and the grasp type. The areas where the different fingers touched the rear surface overlapped to a great extent (Fig. 5.2). The thumb was rarely (with one exception) touching the capacitive screen but was often placed on the front's bezel or the vertical sides (Fig. 5.4).

5.3.3 Discussion

The results show that grasps vary a lot between users. The thumb mostly rested on the bezel or on the device side. The fact that participants avoid touching the frontscreen might result from the awareness that touchscreens interpret a touch as a

Fig. 5.4 Thumb position on the front of the device while just holding it

command. As a touch-sensitive surface on the back of the device is still unusual, that strategy may not apply for a touchscreen on the rear, which was touched while grasping. Probably, users change the way they hold the device if back-of-device interaction is more common.

These findings are in line with and extend those from Wagner et al. (2012) who found no predictable grasp pattern for holding tablets. Wimmer (2011) introduced a grasp model that considers five factors to determine how an object is grasped: goal, relationship between user and object, anatomy, setting, and properties of the object. However, the object in the presented grasp observation is always the same; users have different hand sizes and force. It seems impossible to control the five factors proposed by Wimmer. Therefore, the way users grasp a device may be unpredictable.

The observed unintended touch events were located close to the vertical edges of the rear device. Thus, the Midas touch problem may occur more often on outer regions of the back of the device than in the center. Midas touch problems on the frontscreen seem to be an exception.

5.3.4 Design Guidelines

Holding a tablet causes already touch events on the back of the device. These have to be understood to distinguishing them from touch gestures:

1. Holding a device triggers unintended touch events on back-of-tablet touchpads.
2. The unintended touch events are located very close to the vertical bezel, if the device is held symmetrically with two hands.
3. The vertical position of unintended touch events is not predictable.

5.4 Accessibility of Interaction Areas

The surface of current devices is mainly touch-sensitive on touchscreens at the front of the device. The surface on the back of devices has only recently been used for embedding touchpads; and it is likely that more devices have that technical feature in the future.

This section aims to define the accessible surface areas on the front in greater detail than Odell and Chandrasekaran (2012), and to identify those on the back of tablets that have not been explored so far. Identifying accessible interaction areas on devices supports design decisions on layout, such as menu bar, button, and widget placement that are commonly accessible via direct touch in all established touch-screen implementations.

In the following sections, a user study is presented, which investigates surface areas that can be touched easily without releasing the device grasp.

5.4.1 Method

To find out to which extent users are able to touch the device surface while holding it, a user study has been conducted to measure the areas of a tablet's surface that can be reached with each single finger and thumb while holding it.

5.4.1.1 Design

17 participants, 9 female and 8 male, aged between 13 and 57 years (mean = 30, SD = 11) that volunteered in the experiment were asked to solve tasks with an interactive prototype. A 5 × 2 within design with repeated measurements was used. The dependent variables were digit and hand. The independent variables were amount of touched pixels, x-positions and y-positions of touch events, handedness, and digit length to analyze if the length of a digit influences the position of the area that can be reached.

5.4.1.2 Task

The participants were instructed to hold the device in landscape format using both hands in a symmetrical grip. During that time participants were standing. The tasks were drawing a large as possible black shape on a blue background through touch. Each digit should be used, starting from the touch position where the digits were resting while holding the tablet with two hands. The participants were solving that task with the thumbs on the front and with all remaining fingers separately on the back of the device. This was repeated five times for each finger of both hands.

5.4.1.3 Apparatus

The interactive prototype consisted of an application that was implemented on an ASUS Eee Pad Transformer TF101 with a screen size of 1,280 × 742 pixels (without bottom menu bar). The entire device has the dimensions of 27.1 cm × 17.1 cm. During the tasks, the touch events were recorded in logfiles. Moreover, a screenshot was saved after finishing each task. When drawing with the thumb, the device was held in the common way with the screen facing the user for allowing the participants to see what regions they have been touched (Fig. 5.5, left). For recording the touch events of the fingers that naturally were placed at the back of the device, the device was flipped so that backside was facing the users (Fig. 5.5, right). To give the visual feedback about the areas that were touched, the drawing application was presented on an external screen from a laptop that was connected via Bluetooth with the tablet.

5.4.1.4 Measurements

The position of a touched pixel is assumed to influence its reachability. The touch events on the tablet were recorded in logfiles. The number of deleted pixels per digit was recorded as well as their x and y-coordinates. With 17 participants, two hands,

Fig. 5.5 Apparatus for recording the accessible areas for each thumb and finger

five trials per hand and per digit, this amounts to a total of 850 data units. Handedness and demographic data were recorded in a questionnaire. Moreover, the length of each finger and thumb of the right and the left hand of each participant were measured. The thumb was measured from its second joint counted from the tip and the fingers were measured from the joint at the palm like in Lange and Windel (2006). After each trial the images that showed the deleted pixel area (black area on the blue screen shown in Fig. 5.5) were saved.

5.4.1.5 Procedure

After an introduction, the participants solved the drawing task five times with each digit per hand. Nine of the participants started with their dominant, eight with the other hand. All participants interacted with the device in standing position. After completing the tasks, the participants filled in a questionnaire.

5.4.2 Results

The interpretations of the data gathered in the study include the analysis of the size and position of the accessible areas per hand and digit. Moreover, tablet accessibility diagrams are presented where the tablet accessibility is analyzed in dependence of the digit length.

The accessible area was described through the following of the touch events recorded during the experiment: size, position, and range along the x- and y-axes. The size was calculated as the number of touched pixels of the area that were drawn or deleted via the touch points. The minimal and maximal distances from the edges (minX, minY, maxX, maxY) were measured in pixels to be the distance from the top and the left screen border. The ranges between the minimal and maximal distances from the edges were calculated through subtracting both distances (rangeX = maxX − minX, rangeY = maxY − mixY).

The means and standard deviations of the dependent variables per digit are presented in Table 5.2 (without distinguishing between hands as hand was not significantly influencing the variables, as described below).

ANOVAs were used to show whether hand or digit type had a significant influence on the touch position that could be reached per digit. Repeated measure ANOVAs with *hand* and *digit* as within-subject factors using a 5 % significance level showed a significant difference for the dependent variable pixel ($F_{4,240} = 7.355$, $p < 0.001$), rangeX ($F_{4,269} = 5.751$, $p < 0.001$), minX ($F_{4,325} = 7.818$, $p < 0.001$), maxX ($F_{4,229} = 8.476$, $p < 0.001$), rangeY ($F_{4,262} = 12.786$, $p < 0.001$), minY ($F_{4,243} = 74.592$, $p < 0.001$) and maxY ($F_{4,243} = 35.093$, $p < 0.001$) only for the factor *digit*. Thus, while the type of *digit* (index, middle, ring, little finger or thumb) had a significant influence on deleted pixels and deleted area parameters (see Fig. 5.6); the *hand* the area was deleted with did not.

Table 5.2 Means and standard deviations for the dependent variables pixel, rangeX/Y, minX/Y and maxX/Y for the independent variable digit (in pixels)

Digit	Pixel		minX		maxX		rangeX		minY		maxY		rangeY	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Thumb	61,539	3,509	12	9	240	11	229	9	168	10	612	8	444	14
Index	58,650	3,545	40	9	257	11	217	9	140	10	547	8	408	14
Middle	60,262	3,545	71	9	302	11	231	9	188	10	594	8	406	14
Ring	50,354	3,544	71	9	288	11	217	9	291	10	648	8	357	14
Little	39,455	3,507	61	9	245	11	184	9	362	10	683	8	323	14

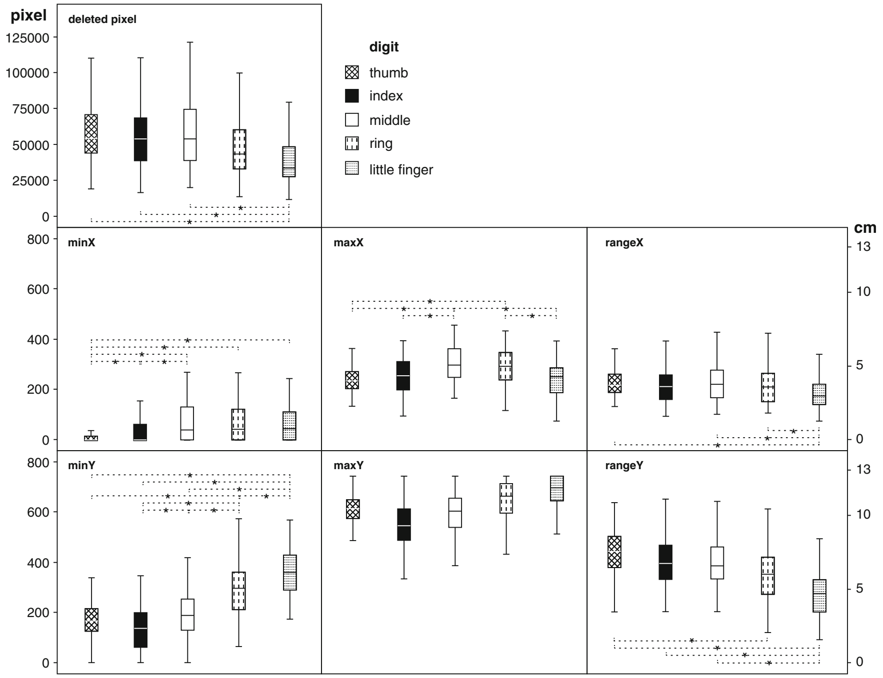

Fig. 5.6 Boxplots for the dependent variables: sum of deleted pixels, distance of access areas front the edges (minX, maxX, minY, maxY) and range between min and max. Significant differences are marked with * as shown in Table 5.3

Regarding the *hand*, no significant results were observed for any of the parameters pixel, rangeX, minX, maxX, y-range, minY, and maxY, as the *p*-value was always equal or higher than 0.673. Moreover, no significant interaction effect of *hand*digit* was found for the dependent variable pixel, which would otherwise indicate that a certain *digit* performed better with a certain *hand*, for instance the dominant one which may have been expected.

Sidak-corrected pairwise comparisons indicated significant differences for deleted pixels per *digit* only between little finger versus thumb, index finger, and middle finger (Table 5.3 and Fig. 5.6). The widths of the deleted areas (rangeX) differed significantly for the little versus thumb, middle, and ring finger. The deleted areas showed significant different heights for thumb versus ring and thumb versus little finger, and also for little versus index finger and little versus middle finger.

The post-hoc tests showed that the averages of the minimal distance of the deleted areas from the vertical edges (minX) differed significantly between the thumb and all fingers. Moreover, the areas that were deleted with the index and middle finger differed significantly in their average closeness to the vertical edge. The furthest points from the vertical edges that were touched with each *digit* were measured with the variable maxX, which was significantly different between the thumb versus middle and ring finger.

Table 5.3 Sidak-corrected pairwise comparisons of *p*-values for the dependent variables pixel, rangeX/Y, minX/Y and maxX/Y for the independent variable digit, significance with a significance level of 0.05 is marked with *

$Digit_i$	$Digit_j$	Pixel	minX	maxX	rangeX	minY	maxY	rangeY
Thumb	Index	0.999	0.021*	0.661	0.920	0.281	0.648	0.200
	Middle	1.000	0.000*	0.000*	1.000	0.865	1.000	0.398
	Ring	0.213	0.000*	0.005*	0.987	0.000*	0.998	0.000*
	Little	0.000*	0.000*	1.000	0.002*	0.000*	0.906	0.000*
Index	Thumb	0.999	0.021*	0.661	0.920	0.281	0.648	0.200
	Middle	1.000	0.009*	0.000*	0.817	0.004*	0.625	1.000
	Ring	0.612	0.091	0.148	1.000	0.000*	0.999	0.088
	Little	0.001*	0.612	0.994	0.117	0.000*	1.000	0.000*
Middle	Thumb	1.000	0.000*	0.000*	1.000	0.865	1.000	0.398
	Index	1.000	0.009*	0.000*	0.817	0.004*	0.625	1.000
	Ring	0.149	1.000	0.833	0.847	0.000*	0.990	0.021
	Little	0.000*	0.993	0.000*	0.002*	0.000*	0.925	0.000*
Ring	Thumb	0.213	0.000*	0.005*	0.987	0.000*	0.998	0.000*
	Index	0.612	0.091	0.148	1.000	0.000*	0.999	0.088
	Middle	0.149	1.000	0.833	0.847	0.000*	0.990	0.021
	Little	0.075	0.954	0.000*	0.013*	0.000*	1.000	0.247
Little	Thumb	0.000*	0.000*	1.000	0.002*	0.000*	0.906	0.000*
	Index	0.001*	0.612	0.994	0.117	0.000*	1.000	0.000*
	Middle	0.000*	0.993	0.000*	0.002*	0.000*	0.952	0.000*
	Ring	0.075	0.954	0.000*	0.013*	0.000*	1.000	0.247

The average distances of the deleted areas from the horizontal top edge showed significantly different results between ring finger and all others, also between little finger and the rest as well as versus index and middle finger. No significant difference was found for the closeness of the deleted areas to the bottom edge (maxY). Thus, touch accessibility for all digits seems not to vary horizontally.

The saved images that show the deleted pixels were used for generating heatmaps by putting the black areas with a transparency level of 4 % per layer one above the other (Fig. 5.7).

While the little finger performs worst (Fig. 5.6), and motions of the ring finger cause motions of neighbor fingers (Vardy 1998), the index and middle fingers are proposed to be appropriate for back-of-device interaction (Chap. 3 and Wolf et al. 2011b). Thus, only heatmaps of the index and middle fingers are merged for visualizing the accessible areas in back-of-device interaction (Fig. 5.7, bottom left).

The heatmaps for each digit have curved borders towards the vertical middle of the tablet. Moreover, the heatmaps provoke the suggestion that the device bezel was touched as well because the shape of the heatmaps appears to be cut on the vertical screen borders. However, that data was not recorded in the logfiles; this trend is also shown in the floor effects of the boxplots of minX for thumb and index finger (Fig. 5.6).

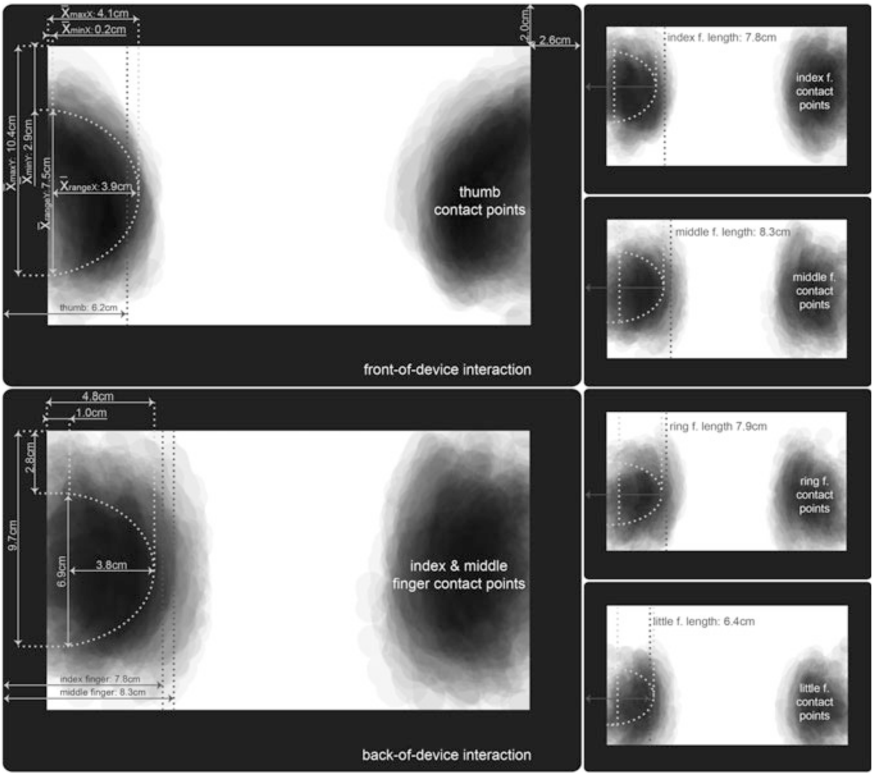

Fig. 5.7 Heatmaps of touch areas per digit and median of digit length. The heatmaps of the fingers on the back of the device are shown in see-through manner. For back-of-device interaction, just the heatmaps of the index and middle finger are merged as these are recommended for back-of-device interaction (Chap. 3, Wolf et al. 2011b)

The middle area of the tablet remained untouched. For analyzing if the digit length influences the degree of tablet accessibility per digit, the medians of digit length were calculated for the female (thumb = 6.2 cm, index finger = 7.5 cm, middle finger = 8.0 cm, ring finger = 7.5 cm, little finger = 6.2 cm) and for the male participants (thumb = 6.7 cm, index finger = 8.0 cm, middle finger = 8.6 cm, ring finger = 8.2 cm, little finger = 6.4 cm). All medians of the participants' digit length fit the range between the 50th and 95th percentiles of Germans' digits (Lange and Windel 2006 and as shown in Table 5.1) and thus, their hand size is representing the average German one. The accessibility of the interaction areas is compared with the digit lengths of the participants through drawing the digit lengths into the heatmaps (Fig. 5.7). For that comparison, the medians of all participants' digit lengths are used (thumb: median = 6.2 cm, SD = 0.4 cm; index finger: median = 7.8 cm, SD = 0.6 cm; middle finger: median = 8.3 mm, SD = 0.7 cm; ring finger: median = 7.9 cm, SD = 0.7 cm; little finger: median = 6.4 cm, SD = 0.5 cm).

For reaching positions of maximal distance to the device edges, digits of the grasping hand have to be stretched. The maximal reachable distance at the touchscreen was equal 1.10 time the thumb's length. The maximal distances at the back of the device are for the index finger 0.93 time its length, for the middle finger 0.95 times its length, for the ring finger 0.95 times its length, and for the little finger 1.06 times its length.

Touching very close areas requires users to flex the joints of the digits. The areas that are very closest to the device edge (and to the palm) are less often touched than those a bit further away. In summary, positions, which are located at minimum a bit further away than the vertical bezel as well as at maximum as far away as the digit's length are accessible for direct touch while grasping a device.

5.4.3 Discussion

Here the findings on front- and back-of-device surface accessibility for direct touch are discussed with the aim to formulate design implications for touch-based interactions with tablets. To do so, at first the results are summarized; then the results of related works as well as the results of the initial observation (Sect. 5.3) are compared with the results of this study; and afterwards, design recommendations are concluded. In the end, the limitations of the study are discussed.

5.4.3.1 Summary of the Results

Analyzing the collected data indicated no difference between both hands. The accessible areas for both hands are symmetric for touchscreen and for back-of-device interaction. The areas that can be reached with each digit differ significantly in position (recorded via min/max x and y-positions of touch) and in size (recorded in amount of deleted pixels and range). While the thumb reaches positions close to the vertical bezel, the fingers' closest touch is further away from the bezel. Moreover, they access larger distances from the frame. That is especially the case using the middle finger as it is the longest and the maximal reachability depends on digit length. The distance a digit can reach via direct touch is similar to its length. While the little and ring fingers lack in performance, the index and middle fingers allow users to access areas as large as with the thumb. Both, the index and the middle finger are flexible while holding a device (Wolf et al. 2011b). The sum of both accessible areas results in an interaction area for back-of-device interaction that is larger than the interaction area on touchscreens.

The results relate to works on interaction areas for touchscreen interaction (Odell and Chandrasekaran 2012; Trudeau et al. 2012) and for back-of-device interaction to previous works (Chaps. 3 and 4, Wolf 2011) as well as to the findings gained in Sect. 5.4.2.

5.4.3.2 Front-of-Device Interaction Areas

The results presented here confirm the findings of Odell and Chandrasekaran that the center of tablet touchscreens is not accessible with grasping hands. Moreover, the presented results show that the limit of reachability is defined by the digits' length. For positions very close to the vertical edges, our findings are different from those of Odell and Chandrasekaran. They present interaction areas that extend the touch-screen of a tablet and state that the bezel is also accessible through direct touch. However, the heatmaps (Fig. 5.7) showed that some participants touched the vertical bezel; statistical analysis indicated that a minimum distance of 2.8 cm was in average the closest distance from the device edge that could be touched. Assuming, that the palm was not moved a lot, one could assume the digits were bent a lot for reaching very close positions and stretched for accessing point far away. The hard accessibility of very outer target can be explained through findings of Trudeau et al. (2012). They found for one-handed phone interaction that the thumb performs best when its pose is relaxed, neither strongly bent nor completely stretched.

The results presented here show that areas are accessible that are located between points near the bezel (that require the joints to be much flexed) and points that are a bit less away than a digit's length (to reach these points a digit has to be stretched). However, according to Trudeau et al., the minimum and maximum of the accessible area may lack in usability and an ergonomic optimal distance for touch interaction is located in between both extreme values.

5.4.3.3 Back-of-Device Interaction Areas

Similar to the presented results for front-of-device accessibility, the results for back-of-device interaction show that the center of a tablet cannot be touched with grasping hands. No work has been done in investigating back-of-device accessibility so far; but Chap. 3 (and Wolf et al. 2011b) explored the manual ability of fingers to perform gestures with grasping hands. It was shown that (beside the thumb) the index and middle fingers are appropriate for gesture execution while grasping. The findings presented here identify also that the index and the middle finger are best flexible and perform best in terms of accessing most areas on the back of a held tablet. Thus, these fingers are most appropriate for back-of-device interaction with grasping hands.

This is in line with the presented results as the index and middle finger perform equally well as the thumb and significantly better than the ring and the little finger.

Excluding ring and little fingers from back-of-device interaction allows them to ensure a stable tablet grasp while the index or middle fingers might actively be used for executing gestures.

As shown in Sect. 5.3, holding a tablet causes unintended touch events on the back of the device. The positions of unintended touch events are located within the accessible area. Thus, there is a need to distinguish unintended touch events from intended gesture commands. The positions of unintended touch events have been shown to be unpredictable (Sect. 5.3). Thus, other parameters than positions are needed to distinguish between Midas touch and gesture commands. In Chap. 4, it was shown that touch duration is a promising parameter for Midas touch detection. An alternative solution would be to avoid direct touch commands, such as item selection, and to use location-independent gestures, e.g. shortcut commands instead. Moreover, the use of salient touch feedback for back-of-device interaction could increase the awareness of unintended touch and thereby reduce the Midas touch problem.

5.4.3.4 Limitations

The observation of unintended touch when a device is held (Sect. 5.3) was conducted in another institute than this user study (Sect. 5.4). Thus, different devices were available and used in the experiments (ASUS tablet vs. iPad2). Moreover, just one device was used in the last user study because the design did not require detecting touch events on two sides at the same time. However, it is assumed that the accessibility is not dependent on the weight of the device. Moreover, the measurements are counted from the device edge, and both tablet devices have similar sizes. Thus, the results shown in both studies are comparable.

5.4.4 Design Guidelines

Regarding the definition of appropriate interaction areas, three aspects should be considered:

1. Touchscreen GUI components that are controlled by direct touch with grasping hands should be located in an area that is between 2.8 cm and the thumb's length away from the vertical device edge.
2. Back-of-device components that are controlled via direct touch of grasping hands should be located in an area that is between 3.6 and 0.9 cm the index finger's length away from the vertical device edge.
3. For back-of-device interaction the index and the middle finger are appropriate while the ring and the little finger are not.
4. For back-of-device interaction the Midas touch problem has to be considered, e.g. through just interpreting touch events shorter than a second or through avoiding direct touch commands.
5. Widgets that are controlled via vertical drag gestures should be shaped like a bow those center points are located on the vertical device bezel.

5.5 Conclusion and Contribution

5.5.1 Conclusion

This chapter was motivated to address two research gaps: At first, interaction areas at tablets' touchscreens are still just rarely investigated; and no research was done for exploring interaction areas on the rear side of tablets. Secondly, the Midas touch problem is a challenge in designing back-of-device interactions, which also is not explored so far.

The work presented here precisely defined interaction areas on both sides of tablets. Constraints, such as the lack in accessing the center areas and the risk to accidently trigger touch event are explored and design recommendations for GUI layouts and for avoiding the Midas touch problem are presented.

5.5.2 Contribution

This chapter provides the following contribution:

- Insights about the way users grip a tablet are provided and areas that are likely to be unintentional touched while the device is held are presented in a diagram.
- Accessible areas on the surface of a tablet are presented for touch on the front and the back of the device for each digit.
- Interaction areas for front- and back-of-device interactions are proposed and guidelines that intend to consider these interaction areas as well as to avoid Midas touch problems are provided.
- The second study described in this chapter is published under Wolf et al. (2014b).

Chapter 6
Front- and Back-of-Device Pointing with Direct Touch

This chapter evaluates the performance of target acquisition through direct touch on the entire interaction areas and provides ergonomic insight about the hand posture when selecting targets.

6.1 Ergonomics in Touch Interaction

However, touch sensors can cover the entire surface of a tablet devices, such as the front as well as the rear side (Wigdor et al. 2007), holding a tablet and executing touch gestures has several ergonomic shortcomings. In Chap. 5, it was shown that the interaction areas in the center of both sides of tablets are hard to reach. Thus, this chapter addresses the two-handed tablet interaction and the challenge of target acquisition while keeping the grip.

To do so, a method has been chosen that allows for analyzing target selection time over a grid of positions all over the front and the back of a tablet. To gain deeper insights about ergonomics while selecting targets that seem to be more difficult, a kinesthetic hand model is recorded while the experiment ran to enrich information being measurable with touch-sensitive surfaces.

Many studies have been conducted about touch interaction (e.g. Forlines et al. 2007; Hoggan et al. 2013; Holman et al. 2013; Karlson and Bederson 2007; Oulasvirta et al. 2013; Wobbrock et al. 2008); among them, all of them use 2D touch information as the only source of measurements. The information that is recordable with touch-sensitive surfaces (the mainstream technology to detect touch) is triggered by skin contact with the surface and contains position data.

Recently it was shown that touch cannot sufficiently be described with merely 2D information (Holz and Baudisch 2011; Holz and Baudisch 2013). Touch is a 3D event, which also contains information about the incoming angle of a finger, the bend angles of joints, and the configuration of the hand. It is also known that the position of fingers influences the position or flexibility of neighbor fingers (Vardy 1998). In the past when conducting studies on touch gestures, data was missing and thus, previous experiments lack a full understanding of how touch works in the 3D space.

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DOI 10.1007/978-3-319-13981-4_6

Experiments have been conducted that show that for one-handed phone interaction, the best touch position is where the thumb is neither completely stretched nor maximal bended (Park and Han 2010; Trudeau et al. 2012). These findings can (due to the influence of the form factor on pointing performance) neither be transferred to interactions with tablet devices, nor to back-of-device interaction with the index finger pointing at targets.

The aim of this chapter is to fill the aforementioned gap in understanding touch-based target acquisition on both, the touchscreen as well as on touchpads on the rear of tablets. Inspired by Kawano et al. (2007), a method is applied, which equips the hands with inertia sensors. These sensors allows for recording a 3D model of the whole hand while data of touch events is collected in pointing tasks. The 3D kinematic measurements were used to analyze 3D hand kinematics during target acquisition with a hand-held tablet. This adds 3D information to common experiment measurements with touchscreens and touchpads; and thereby the expressiveness of experimental data will be enriched. Thus, information about hand configuration and joint orientation is gathered in addition to established 2D touch data that is sensed through touch contact on interactive surfaces. In a controlled experiment, which investigated target selection times using hand-held tablets, it is shown that more insights in gesture interaction are gained using this approach than with a traditional approach utilizing solely 2D information. This leads to a better understanding of the pointing ergonomics on devices being operated by the hand grasping it. These ergonomic insights are used as a basis for concluding design guidelines for front- and back-of-device pointing techniques executed with the grasping hand.

6.2 Method

Pointing and target selection at both, the touchscreen and a touchpad on the back of a tablet while the device is held with two hands has to the author's best knowledge not been investigated thus far. This defines a research gap that will be addressed in the following experiment.

6.2.1 Design

This study was designed as 2 × 2 × 2 within-subjects design with repeated measurements where 16 participants (5 female and 11 male participants, 28.4 year in average (SD = 4.8), 14 right- and 2 left-handed) volunteered. The independent variables were *hand* (left and right hand), *augmentation* (with and without augmenting the participants' hands with motion sensors), and device side (whether pointing is executed on the front or on the back side of the device). The dependent variables were target selection time, error rate, hand orientation as well as the

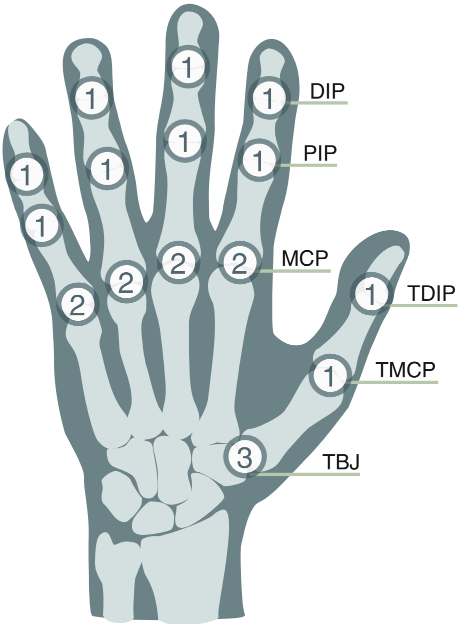


Fig. 6.1 Human hand with joint names and degrees of freedom (DOF) per digit. The hand root has 3 DOF, the thumb has 5 DOF, *3* at the bottom joint (thumb basal joint: TBJ), *1* at the middle (thumb metacarpophalangeal joint: TMCP) and *1* at the top joint (thumb distal interphalangeal joint: TDIP), and the index finger has 4 DOF, *2* at the bottom (metacarpophalangeal joint: MCP), *1* at the middle (proximal interphalangeal joint: PIP), and *1* at the top joint (distal interphalangeal joint: DIP)

rotation angles for each joint of the digit that is used for pointing. For touchscreen pointing this is the thumb; and for back-of-device pointing, the index finger was used. The joints of the thumb have 5 degrees of freedom (DOF) as the lowest joint (TBJ) has three DOF and both upper joints (TMCP, TDIP) have just 1 DOF each (as shown in Fig. 6.1). The two upper joints of the index finger (PIP, DIP) have also 1 DOF each. Its lowest joint (MCP) has just 2 DOF.

6.2.2 Task

The task was to select targets with grasping hands that held a tablet in landscape format with a bimanual symmetric grip. Participants selected targets in the same manner under all 8 conditions: with and without sensory augmentation, with each hand, and on both device sides. Each selection task begun by pressing a start button, positioned at X = 64 px (11 mm), Y = 374 px (63 mm) for the left-handed and at X = 1,216 px (206 mm), Y = 374 px (63 mm) for the right-hand condition. Please note that all pixel and mm measures in this chapter are always counted from the left

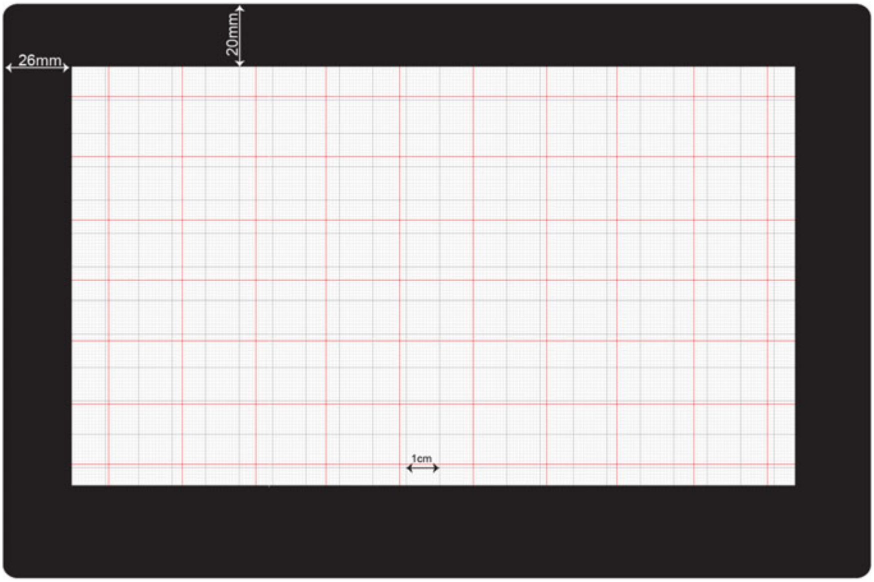


Fig. 6.2 Apparatus: tablet device including the 7 × 10 grid drawn in *red* where the targets occur

upper corner of the screen; and that the frame, which is not included in the mm-measurements has a height of 20 mm and a width of 26 mm. During the frontscreen conditions, the button was accessible through touching the frontscreen; for the back-of-device conditions a touchpad on the rear was used to select the start button. The targets appeared after the start button was released in random order 5 times per target size equally distributed over the tablet screen on a 7 × 10 grid (as shown in Fig. 6.2). The targets were sized 28 px/5 mm, 42 px/7 mm, and 56 px/10 mm inspired by Parhi et al. (2006) and Hasan et al. (2012) and with the intention to represent the size of typical tablet content, such as text and buttons. Due to the limited access of targets at the left side of the screen for the right hand and of targets on the right hand side of the screen for the left hand, the targets for each hand were displayed on the 6 of 10 closest vertical grid lines. This overlap served to better understand target selection in the center area, which is hard to reach. The instruction for solving a task was to select the targets as quickly as possible.

6.2.3 Apparatus

Two apparatuses were employed in the experiment, as shown in Fig. 6.3. Apparatus 1 was a tablet sandwich to present the experimental task and to record 2D data. Apparatus 1 consisted of two tablet devices glued together by their rear sides and connected via Bluetooth (inspired by Shen et al. 2009). This allowed for sensing

Fig. 6.3 Real-time whole hand modeling using 9 DOF digit-mounted motion sensors allows recording a dynamic hand model while studying touch-based interaction

touch events on the back of the apparatus and to update the GUI of the device at the front accordingly. The size of the screen was 1280 × 742 pixels (without bottom menu bar) that are 21.7 cm × 13.6 cm.

Apparatus 2[1] is a system that records 3D data of the hand consisting of four wearable sensor sticks (multiplexed Magnetic Angular Rate Gravity (MARG) sensors that contain 3 degree-of-freedom (DOF) acceleration sensors (ADXL345) and 3 DOF magnetometers (HMC5883L) in combination with 3 DOF gyroscopes (ITG3200) for joint orientation tracking), a micro controller (Arduino Nano V3) and a PC running 3D hand model recording software. This approach was inspired by Kawano et al. (2007) who were using accelerometers, gyroscopes and magnetometers for analyzing 3D knee kinematics for estimating all knee joint angles, flexion/extension, and internal/external rotation. Kawano et al. (2007) evaluated the estimated angles numerically by comparing the results with an optical motion system. In the experiment presented here, an inertia sensor-based 3D tracking system was favored against optical motion systems, such as Vicon. Optical systems are great for tracking free-hand mid-air gestures, but may cause occlusion problems by the held tablet device.

The 3D hand model recording software used here is capable of tracking the configuration of single finger joints at over 30 Hz in real time. To do this, a Java-based PC-Application fuses the raw sensor data from the accelerometer, gyroscope, and magnetometer. While recording, one sensor stick is always attached to the back of the hand and serves as a reference orientation for the whole hand. The reference is used to calculate the digit orientation relative to the hand root.

[1] Apparatus 1 was built by John Mercouris during his DAAD RISE funded internship at TU Berlin, which was supervised by the author. Apparatus 2 was built by Christopher-Eyk Hrabia during his Master's thesis, which was supervised by the author.

Three sensor sticks are mounted at each individual segment of the thumb or the index finger (depending on the condition) using rings and a shortened glove to keep the thumb- and fingertips uncovered and avoid touch recognition problems on the tablet's touchscreen. The sensors are attached to the joints through Velcro that allows for rapid switching between augmenting the thumb for the front conditions and the index finger for the back-of-device conditions during the experiment. The software of Apparatus 2 models the orientation of the entire hand as well as the configuration of every digit (thumb or index finger) segment that results in the whole digit pose.

Inertia sensors are known to cause drift problems. In the hand model, a drift of joint rotations is corrected using the Mahony et al. (2008) and Madgwick et al. (2010) filters that fuse the data of all three sensors and corrects the rotation drift of the gyroscope. The gyroscope data is used for detecting how much each digit joint is rotated compared to their neighbor joint and the hand root. Drift can influence the angles recorded with the tool, which would add noise to the joint angle data. Thus, before the experiment, the hand model recording software was tested through drawing angles of 30°, 45°, and 60° on paper and bending exemplarily the two upper joints of the thump (TDIP, TMCP, see Fig. 6.1) according drawn angles 40 times per angle (30°/45°) as well as the two upper joints of the index finger (DIP, PIP) according drawn angles (45°/60°). Repeated measurement ANOVAs show that the maximum joint rotation angles did not differ significantly from angles drawn on paper ($F_{1,279} = 1.088$, $p = 0.767$). This evaluation ensured that the angles recorded with the hand model software are about the same as the actual angle of the joints.

Both apparatuses, the tablet sandwich and the hand model recording software, are able to record logfiles. To synchronize both logfiles, the tablet sends "event labeling" messages to the software on the PC via WiFi when the start button is pressed as well as when a target is hit.

6.2.4 Measurements

The interaction time and the 2D touch events for selecting each target were recorded in logfiles on the front tablet device. The raw data of four sensor sticks with 9 DOF motion data each as well as the absolute hand root orientation and the rotation angle of each thumb joint, which is the base of the real time hand model, were recorded by the 3D software. In summary, data of 80,640 trials on the tablet as well as on the PC were recorded (16 participants × 2 hands × 2 augmentation conditions × 2 device sides × 3 target sizes × 42 target positions per condition and hand × 5 repeated presentations per target size at each position). Finally, participants answered questionnaires about their gender, age, and hand dominance.

6.2.5 Procedure

After explaining the task and a short training, the tasks were solved in counterbalanced order, which means that half of the participants were solving the pointing task with each hand first without augmentation and afterwards with having the sensors attached to their hands. The last eight participants solved the task at first with and then without augmentation. Within these conditions, device side and hand was counterbalanced as well. While front-of-device interaction sensors were attached to the thumb; and during back-of-device interaction, the index finger wore sensors. One sensor unit was for both, front- and back-of-device interaction, attached to the back of one's hand. At the end, the participants filled in a demographic questionnaire.

6.3 Results from 2D Data

Following questions guided the analysis of the data recorded in logfiles on the tablet:

Q1: Do the performance measurements require different treatment for each *hand,* in accordance with the handedness of the participant or in regard the *side of the tablet* (front vs. back) on those the pointing gesture is placed?

Q2: As a lack of influence of wearing the sensory *augmentation* on the objective performance measurements would permit considering all data for performance analysis, it was questioned if the hand's augmentation affects the 2D results.

Q3: As only trials were considered where the target was hit with the first touch, the other trials were defined as error and excluded from the data set. For calculating the *error rate*, the question is: how many targets per hand and target size were not selected on the first try?

Q4: After filtering the data in regard to ***Q1***, ***Q2***, and ***Q3***, the question is: How does the *target size* effect the target selection time?

Q5: Finally, the 2D data is analyzed to determine if the *target position* affects the target selection time?

6.3.1 Q1: Handedness

Repeated measure ANOVAs using a 5 % significance level indicated that selecting a target was significantly faster with the *dominant hand* ($F_{1,46894175} = 14.776$, $p < 0.001$, $\text{mean}_{dominant} = 1{,}096$ ms, $\text{mean}_{non\text{-}dominant} = 1{,}148$ ms).

Because of the significant influence of the dominant hand on the target selection time, in the further results the factor *hand* was differentiated between dominant and none-dominant (instead of right and left). Thus, for any analysis that includes absolute target positions, just the data sets from the 14 right-handed participants will be considered. The data sets of both left-handed participants will be ignored as two data sets are too few to allow for quantitative analysis.

6.3.2 Q1: Hand

Repeated measure ANOVAs showed that for the right handed participants selecting a target was significantly faster with the *right hand* than with the left ($F_{1,5.325e+7} = 44.013$, $p < 0.001$, $mean_{right} = 1{,}077$ ms, $mean_{non\text{-}dominant} = 1{,}151$ ms).

Because of the significant influence of the hand on target selection time, and as targets in the center areas were selected with both hands in separate conditions; for further analysis on the influence of target position on target selection time, the calculations will be made with subsets of the data for each hand separately (Sect. 6.3.7).

6.3.3 Q1: Device Side

Whether targets were selected on the front or on the back of the device affected the target selection time significantly ($F_{1,1.685e+09} = 531.073$, $p > 0.001$). Targets were selected in average about 1.7 times faster on the front of the device compared to the rear ($mean_{front} = 837$ ms, $mean_{rear} = 1{,}420$ ms) that is shown in Fig. 6.4.

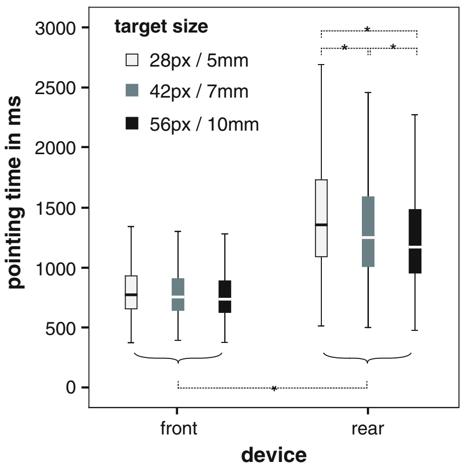


Fig. 6.4 Boxplots: target selection time per target size on both the front and the rear of the device

6.3.4 Q2: Augmentation

Wearing the inertia sensors during the target selection task did neither slow down the interaction (*augmentation:* $F_{1,3985492} = 1.256$, $p = 0.262$, $\text{mean}_{standard} = 1{,}051$ ms, $\text{mean}_{augmented} = 1{,}179$ ms), nor increased the error rate ($\text{errorRate}_{standard} = 17.8$ %, $\text{errorRate}_{augmented} = 16.0$ %). Thus, wearing additional sensors had not significantly influenced target selection performance. Therefore, for further analysis the complete data, including both the sets recorded while the participants' hands were augmented and those while no sensors were worn, can be considered. Moreover, no interactions between *augmentation*device side* ($F_{1,7059085} = 2.224$, $p = 0.136$) and *augmentation*dominating hand* ($F_{1,323917} = 1.102$, $p = 0.749$) influenced the target *selection time* significantly.

6.3.5 Q3: Error Rate

When comparing the error rates per target location, only the data from the right-handed participants was considered. Pointing at targets on the touchscreen (front side) with the left hand caused an *error rate* of 14.4 % (target size of 28 px/5 mm: 20.1 %, of 42 px/7 mm: 13.6 %, of 56 px/10 mm: 8.9 %); and using the right hand resulted in an *error rate* of 12.9 % (target size of 28 px/5 mm: 18.9 %, of 42 px/7 mm: 12.0 %, of 56 px/10 mm: 7.8 %).

Pointing at targets on the rear caused a 13.1 % *error rate* (target size of 28 px: 13.8 %, of 42 px: 13.3 %, of 56 px: 12.1 %) using the left hand and a 17.1 % *error rate* (target size of 28 px: 19.0 %, of 42 px: 17.7 %, of 56 px: 14.1 %) when the right hand was used.

Please note that for all 2D performance analysis (target size, target position), the error trials were excluded and only trials where the target was selected by the first touch event after pressing the start button were considered.

6.3.6 Q4: Target Size

Repeated measure ANOVAs with *target size, device side*, and *dominant hand* as independent and target *selection time* as dependent factor yielded a significant effect of *target size* ($F_{1,28373387} = 28.295$, $p < 0.001$) as well as an interaction effect of *target size*device side* ($F_{1,17619152} = 17.570$, $p < 0.001$) on the target selection performance.

Repeated measure ANOVAs with two subsets of the data, one per *device side*, showed that target selection time differed not significantly between the three *target sizes* for selecting targets at the *front side* ($F_{1,394825} = 1.404$, $p = 0.525$) but for selecting at the *rear side* ($F_{1,45597714} = 44.332$, $p < 0.0015$) as shown in Fig. 6.4.

Despite the high variance in target selection time between the participants, a Tukey post-hoc test with pairwise comparisons yielded significantly different selection times between all three *target sizes* for back-of-device target selection (28 px/5 mm vs. 42 px/7 mm: $p = 0.045$, 42 px/7 mm vs. 56 px/10 mm: $p < 0.001$, 28 px/5 mm vs. 56 px/10 mm: $p < 0.001$; with the average times of $\text{mean}_{rear\_28\ \text{px/5 mm}} = 1{,}534$ ms, $\text{mean}_{rear\_42\ \text{px/7 mm}} = 1{,}418$ ms, and $\text{mean}_{rear\_56\ \text{px/10 mm}} = 813$ ms, Fig. 6.4).

6.3.7 *Q5: Target Position*

Please note that (due to the influence of the hand's dominance on target selection time) the sub-set of right-handed participants were used for analysis of the influence of the target *position* on *selection time* as in this case it matters if the dominant hand is placed at the right or at the left device side.

However, traditional pointing studies (following the setup of Fitts (1954)) are designed as 1-dimensional action; the pointing direction in this study had two, an x- and a y-dimension. Thus, the influence of the absolute (x-/y-coordinates) *target position* on target *selection time* is analyzed. Target positions refer to coordinates on the tablet counted from the upper left corner.

Handedness, hand, and device side influence target selection time significantly (Sects. 6.3.1–6.3.3). Thus, for analyzing the influence of *target position* on *selection time*, repeated measurement ANOVAs were calculated with four sub-sets of the data, one set for each hand those were again split into sub-sets of both, touchscreen pointing released with the thumb and back-of-device pointing released with the index finger.

For touchscreen pointing (front) with the right hand (of right-handed participants), ANOVAs yielded a significant difference in target *selection time* depending on the horizontal x-position of the target ($F_{5,1.342e+6} = 3.194$, $p = 0.018$) but not regarding the vertical y-position ($F_{6,3.033e+6} = 1.351$, $p = 0.909$).

For touchscreen pointing (front) with the left hand (again of right-handed participants), ANOVAs indicated a significant difference in target *selection time* regarding both, the x-position ($F_{5,1.847e+7} = 2.576$, $p = 0.025$) as well as influenced by the y-position ($F_{6,3.033e+6} = 1.351$, $p = 0.909$).

For back-of-device pointing at touchpads (rear) with the right hand, ANOVAs showed that *selection time* is significantly influenced by the x-position of the target ($F_{5,3.059e+7} = 6.474$, $p < 0.001$) as well as by y-position ($F_{6,2.012e+7} = 3.530$, $p = 0.002$).

For back-of-device pointing at touchpads (rear) with the left hand, ANOVAs indicated a significant difference in target *selection time* regarding both, the x-position ($F_{5,4.531e+7} = 6.977$, $p < 0.001$) as well as dependence on the y-position ($F_{6,1.701e+7} = 2.171$, $p = 0.043$).

In summary, the x-position of a target significantly influenced the target selection time in all cases (selecting with right and left hand through pointing at a touchscreen as well as at a touchpad on the rear of the device); and the y-position always affected the target selection time significantly except when the left hand was used for pointing on a front sided touchscreen.

However, no significant difference was found for the influence of y-position in target selection time when pointing with the left hand on the touchscreen (front); Tukey post-hoc tests indicated for this condition still a marginal faster pointing time for targets located in the lower vertical (486 px/82 mm counted from the upper edge) center than if the target is located on the top of the display (54 px/9 mm) as shown in Table 6.1. If using the right hand for pointing at targets on the touchscreen, both most outer positions, the top (54 px/9 mm) and the bottom (702 px/119 mm), take significantly longer than if targets were located closer to the vertical center. However, pointing at targets on the back of the device that are located at top and bottom interaction areas is slower than for targets in center positions; the outer areas that take longer are larger (up to 162 px/27 mm and from 594 px/101 mm onwards counted from the top) for back-of-device pointing than for pointing at the front sided touchscreen.

Post-hoc comparisons using the Tukey test show that targets, located in the center (x-position), take significantly longer in acquisition than targets that are placed closer to the vertical frame edge where the hands are grasping the device (Table 6.2). If the targets are accessed from the front, the center area that required significant longer pointing time is slightly smaller (left hand: 580–709 px/98–120 mm, right hand: ≥580 px/98 mm) than if targets are selected at the rear side where the area with worse pointing performance is larger (451–838 px/76–142 mm).

The pointing performance for each axis is shown in Figs. 6.5 and 6.6. The pointing performance depending on 2D target position is visualized with a 3D plot of time over a 2D grid of target position as shown in Figs. 6.7 and 6.8. Please note that for the overlapping regions (x-position: 98, 120 mm from the left edge), the value from the dominant (right) hand is visualized, as these were smaller than interaction times when using the left hand. This approach is led by the suggestion that pointing with the dominant hand is easier and thus, that may be used for pointing at center areas.

Figures 6.5 and 6.6 visualize that the shortest *selection times* for pointing at both device sides are in the vertical center at the outer *x-positions* 33 and 186 mm; and the longest *selection times* were at the vertical bottom and top at the central *x-positions* 98 mm counted from the left side. Looking at *selection times* of targets in order of their vertical position shows that the outer positions take longest, while the center positions require the shortest *selection times*. These results are significant as shown in Tables 6.1 and 6.2.

Plotting time in 3D over a target position grid (Figs. 6.7 and 6.8) shows that target *selection times* plot in a third dimension over the target *x-* and *y-positions* forms a sink shape for each side accessed with one hand for both *device sides*.

The minimum of target selection time that is surprisingly not positioned closest to the start button but has an optimum at X = 33/186 mm, Y = 64 mm, whereby the start button is located at X = 11/208 mm, Y = 64 mm. From there, the selection time

Table 6.1 Post-hoc pairwise comparisons of target selection time in dependence on the target's y-position

		Y POSITION						
		54	162	270	378	486	594	702px
	mm	9	27	46	64	82	101	119mm
FRONT					**left hand**			
	9		0.9448	0.8324	0.6380	0.0546 .	0.7716	0.999
	27	0.9448		0.9999	0.9937	0.4984	0.9996	0.991
	46	0.8324	0.9999		0.9997	0.7013	1.0000	0.947
	64	0.6380	0.9937	0.9997		0.9290	1.0000	0.817
	82	0.0546 .	0.4984	0.7013	0.9290		0.7717	0.127
	101	0.7716	0.9996	1.0000	1.0000	0.7717		0.914
	119	0.999	0.991	0.947	0.817	0.127	0.914	
					right hand			
	9		0.0021 **	< 0.001 ***	< 0.001 ***	< 0.001 ***	0.0583 .	0.5941
	27	0.0021 **		0.3514	0.8825	0.6372	0.9554	0.3236
	46	< 0.001 ***	0.3514		0.9877	0.9996	0.0325 *	< 0.001 ***
	64	< 0.001 ***	0.8825	0.9877		0.9998	0.3083	0.0183 *
	82	< 0.001 ***	0.6372	0.9996	0.9998		0.1093	0.0026 **
	101	0.0583 .	0.9554	0.0325 *	0.3083	0.1093		0.90956
	119	0.5941	0.3236	< 0.001 ***	0.0183 *	0.0026 **	0.90956	
BACK					**left hand**			
	9		0.2082	< 0.001 ***	< 0.001 ***	< 0.001 ***	0.7238	0.9979
	27	0.2082		0.02523 *	0.0873 .	0.2914	0.9793	0.05007 .
	46	< 0.001 ***	0.02523 *		0.9999	0.9618	0.0011 **	< 0.001 ***
	64	< 0.001 ***	0.0873 .	0.9999		0.9958	0.0065 **	< 0.001 ***
	82	< 0.001 ***	0.2914	0.9618	0.9958		0.0352 *	< 0.001 ***
	101	0.7238	0.9793	0.0011 **	0.0065 **	0.0352 *		0.3507
	119	0.9979	0.05007 .	< 0.001 ***	< 0.001 ***	< 0.001 ***	0.3507	
					right hand			
	9		0.1069	<0.001 ***	<0.001 ***	<0.001 ***	0.0203 *	0.0380 *
	27	0.1069		0.2100	0.0209 *	0.0256 *	0.9979	<0.001 ***
	46	<0.001 ***	0.2100		0.9589	0.9851	0.5288	<0.001 ***
	64	<0.001 ***	0.0209 *	0.9589		1.0000	0.0938 .	<0.001 ***
	82	<0.001 ***	0.0256 *	0.9851	1.0000		0.1175	<0.001 ***
	101	0.0203 *	0.9979	0.5288	0.0938 .	0.1175		<0.001 ***
	119	0.0380 *	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	

*** <0.001, ** <0.01, * <0.05, '.' <0.1

Table 6.2 Post-hoc pairwise comparisons of selection time in dependence on the x-position

		X POSITION									
		64	193	322	451	580	709	838	967	1096	1225px
	mm	11	33	55	76	98	120	142	164	186	208mm
FRONT		left hand									
	11		0.1984	0.9460	0.6905	< 0.001 ***	< 0.001 ***				
	33	0.1984		0.7067	0.0014 **	< 0.001 ***	< 0.001 ***				
	55	0.9460	0.7067		0.1408	< 0.001 ***	< 0.001 ***				
	76	0.6905	0.0014 **	0.14080		0.0278 *	< 0.001 ***				
	98	< 0.001 ***	< 0.001 ***	< 0.001 ***	0.0278 *		0.0085 **				
	120	< 0.001 ***	< 0.001 ***	< 0.001 ***	< 0.001 ***	0.0085 **					
						right hand					
	98						0.0053 **	0.0066 **	< 0.001 ***	< 0.001 ***	< 0.001 ***
	120					0.0053 **		1.0000	0.0967 .	0.2004	0.6919
	142					0.0066 **	1.0000		0.0860 .	0.1816	0.6623
	164					< 0.001 ***	0.0967 .	0.0860 .		0.9995	0.8993
	186					< 0.001 ***	0.2004	0.1816	0.9995		0.9769
	208					< 0.001 ***	0.6919	0.6623	0.8993	0.9769	
BACK		left hand									
	11		0.2108	0.9622	0.9910	0.0531	< 0.001 ***				
	33	0.2108		0.6736	0.0348 *	< 0.001 ***	< 0.001 ***				
	55	0.9622	0.6736		0.6733	0.0020 **	< 0.001 ***				
	76	0.9910	0.0348 *	0.6733		0.1863	< 0.001 ***				
	98	0.0531	< 0.001 ***	0.0020 **	0.1863		< 0.001 ***				
	120	< 0.001 ***	< 0.001 ***	< 0.001 ***	< 0.001 ***	< 0.001 ***					
						right hand					
	98						< 0.001 ***	< 0.001 ***	< 0.001 ***	< 0.001 ***	< 0.001 ***
	120					< 0.001 ***		0.4253	< 0.001 ***	< 0.001 ***	0.0860 .
	142					< 0.001 ***	0.4253		0.0249 *	0.0047 **	0.9543
	164					< 0.001 ***	< 0.001 ***	0.0249 *		0.9962	0.2952
	186					< 0.001 ***	< 0.001 ***	0.0047 **	0.9962		0.1076
	208					< 0.001 ***	0.0860 .	0.9543	0.2952	0.1076	

***<0.001, ** <0.01, * <0.05, '.' <0.1

increases almost symmetrically for both hands (with slightly shorter times for the dominant hand); and has its maximum in the center of the device, which (in contrast to the position of the optimum) is suggested considering Fitts's Law (Fitts 1954). In Fitts' Law, selection time increases over distance (in dependence of target size), which at least for the target positions close to the edges is not the case.

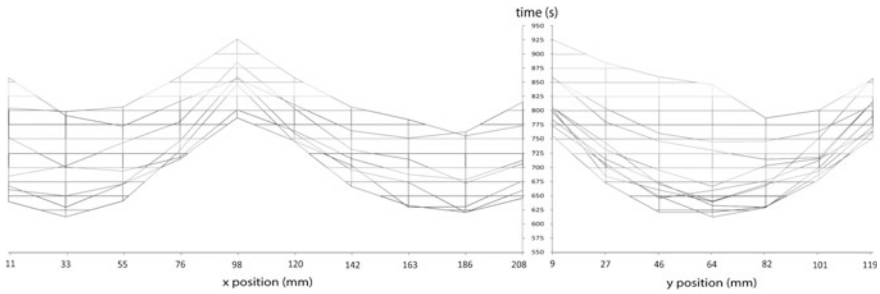


Fig. 6.5 Pointing time per axes for front-of-device target acquisition

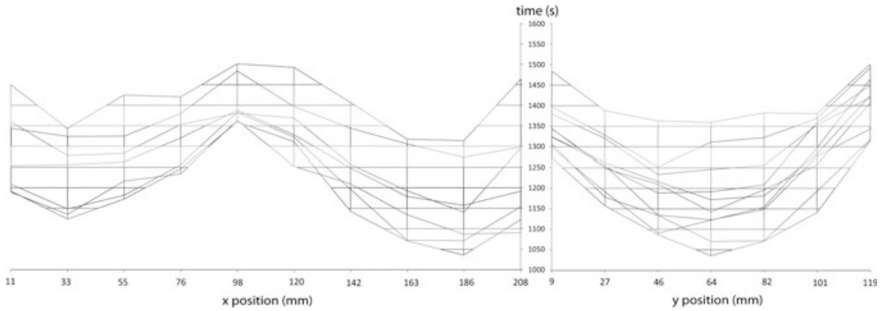


Fig. 6.6 Pointing time per axis for back-of-device target acquisition

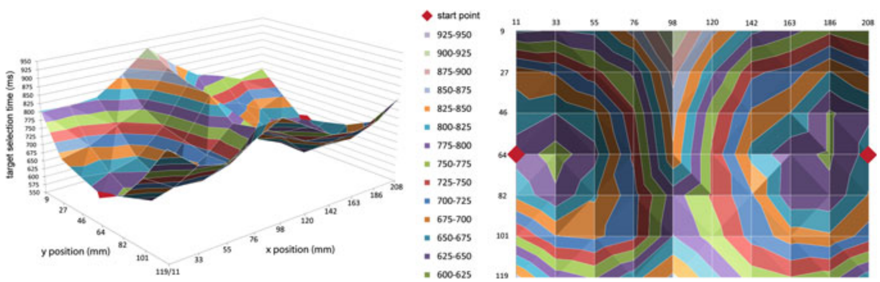


Fig. 6.7 Pointing time (*left* z-axis, *right* heatmap) over position (x-, y-axes) for target acquisition at the front of a tablet

6.4 Discussion of 2D Results

The presented results are in line with Odell and Chandrasekaran (2012) who defined regions close to the vertical edge of a hand-held tablet easy to touch. Moreover, the presented results show that similar areas are well accessible for back-of-device interaction. In contrast to Odell and Chandrasekaran (2012), here detailed analyses are provided on the selection time in dependence on target position.

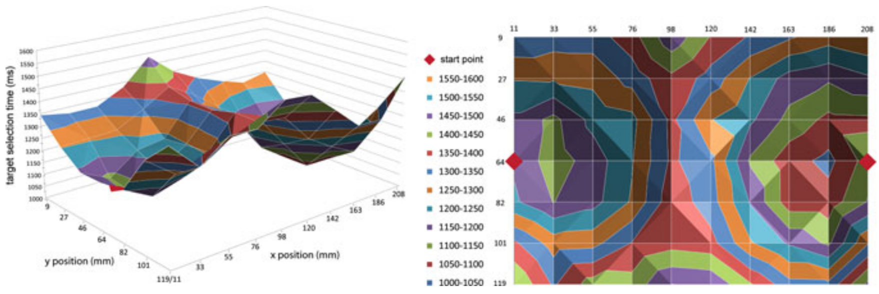


Fig. 6.8 Pointing time (*left* z-axis, *right* heatmap) over position (x-, y-axes in see-through perspective) for target acquisition at the rear of a tablet

Despite the high variance in target selection time between the participants, significant effects of target size on target selection times were found. In contrast to expected selection times, this experiment shows that very short horizontal distances from the edges require surprisingly more time for selections than targets slightly further away. An optimal position for each device side is indicated by the presented data, which leads to shorter selection times than positions closer to the start button.

One reason for unexpected long target acquisition close to the edge where the hand is placed could be that the hand is occluding the target and thus, it takes longer to be seen. For example, targets may appear underneath the thumb. As the phenomenon of longer pointing times for targets that are very close by located to the hand occurs also for back-of-device pointing, this argument can be excluded as pointing at the rear does not cause occlusion problems (Baudisch and Chu 2009).

Because the hand's biomechanics influence its feasibility (Hrabia et al. 2013; Vardy 1998), the presented results provoke the assumption that biomechanic capabilities and limitations of the hand are the reason for the shorter interaction times at the optimal positions versus closer target positions. A suggestion may be that if the joints of the thumb and index finger are bended significantly to reach targets close to the edge (11/208 mm); the joint rotation limitation may be reached. Thus, the selection time may increase due to increasing physical effort compared to when targets are touched that are located slightly further away (33/186 mm from the display's vertical edges). A similar finding was provided by Trudeau et al. (2012) for one-handed interaction with mobile phones. Through tracking the thumb and wrist poses with an optical motion system it was shown that motor performance in target acquisition was greatest when the thumb was in a typical resting posture, neither significantly flexed nor fully extended.

The information recorded in the logfiles of the tablets apparatus of this study does not provide data about the digit joint rotation; but the made assumption can be investigated with additional information about the hand, such as the 3D data that we recorded in parallel to the 2D data using a data glove.

6.5 Results from 3D Kinetic Hand Model

For each target selection trial, data recording the hand movements was gathered. Furthermore, depending on the condition, data measuring the pose and the movements of the thumb for touchscreen pointing and of the index finger for back-of-device pointing was collected. The raw data of the hand model consists of a 3 DOF magnetometer attached to the hand root for modeling the absolute hand orientation and of one 3 DOF gyroscope attached to the hand root (labeled as *root* in Fig. 6.9) as well as to each segment of the thumb (labeled as *TBJ* and *TMCP*, and *TDIP* in Fig. 6.8 and explained in the caption of Fig. 6.1) and to the index finger (labeled as *MCP* and *PIP*, and *DIP* in Fig. 6.9). This data served to track hand and joint rotations for a dynamic model of the entire hand pose with the exact thumb and index finger configuration. The raw data for the hand root and each thumb and index finger segment in angle values (degrees) was translated and synchronized with the logfiles from the tablet apparatus using unique labels as described in the *measurements* section. Incomplete data sets were excluded; and just the data that represents trials where the target was successfully hit with the first touch was considered. Furthermore, the data from the left-handed participants was excluded as hand dominance had a significant influence on the task as shown above. Thus, 13,491 data sets of target selection trials in total were considered for the analyses containing interaction times, 2D touch information as well as 3D hand pose and movement data.

The aim of this analysis is to use the 3D data to help understand the findings gained through analyzing the 2D touch data. Through analyzing the 2D data it was

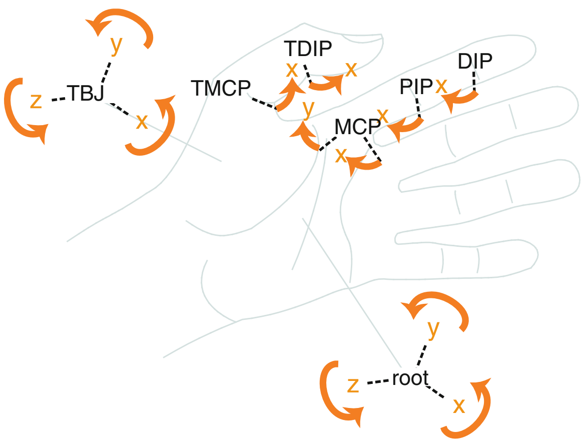


Fig. 6.9 DOF of the hand model: the root of the hand model has 3 DOF; the DOF of the thumb and digit are similar to the motor DOF of the hand (Fig. 6.1), which are 5 DOF for the thumb (3 at TBJ, 1 at TMCP, and 1 TDIP), and 4 DOF for the index finger (2 at MCP, 1 at PIP, and 1 at DIP). The x-/y-motions of the hand root match to position translations on a tablet when this is held like in Fig. 6.3

shown that target selection time depends on the target position (*x-, y-position*). Analyzing the 3D data aims to provide a better understanding of why for example selecting very close targets (in dependence of the start position) takes longer than selecting targets that are slightly further away (especially in the x direction) as this is a contradiction to the established target selection model of Fitts' Law. It was assumed that for closer targets the joints may require to be rotated in an inconvenient way. To investigate the potential influence of joint rotation on pointing performance, the following joint and hand states were analyzed:

Joints rotation (*angle_max*): The average maximum of joints rotations (relative to the joint that is nearer to the hand root or to the hand root itself) for each target position and over all participants while pointing a target. This data is used to investigate if a joint is stressed through a rotation that reaches the biomechanical limit of the joint.

Joint motion (*angle_range*): The amount of joint motions that is calculated as average difference between the maximum and the minimum joint rotation angle per target position across all participants while pointing a target. This data is used to analyze the amount of motion required to select a target, which is interpreted as physical effort.

6.5.1 Touchscreen Pointing

Through ANOVAs it was investigated if a joint of the thumb (labeled in Fig. 6.8 as *TBJ, TMCP*, and *TDIP*) moves significantly more (measured as *angle_range*) while pointing at certain x- and y-positions on the touchscreen. Further ANOVAs were conducted to test if selecting targets on certain x- or y-positions on the tablet's touchscreen influenced the amount a joint is rotated (*angle_max*).

For both hands, the *x-position* affects the entire amount of motion that the bottom thumbs joint (*TBJ*) are executing around their y-axes (*TBJ range_y* of the left hand: $F_{5,2983} = 2.636$ $p = 0.021$, Turkey post-hoc test: X = 33 mm and X = 76 mm: $p = 0.027$ as shown in Fig. 6.10(1); and *TBJ range_y* of the right hand: $F_{5,4273} = 4.953$ $p > 0.001$; Tukey: X = 98 mm vs. X = 186 mm: $p = 0.009$, X = 98 mm vs. X = 208 mm: $p = 0.002$, X = 142 mm vs. X = 186 mm: $p = 0.044$, and X = 142 mm vs. X = 208 mm: $p = 0.012$, see Fig. 6.10(2)). ANOVAs indicated that the x-position affects the rotation of the bottom joint corresponding to the rotation around the x-axis (*max_x* at *TBJ:* $F_{5,4273} = 2.216$ $p = 0.05$; Tukey: 142 mm vs. 186 mm: $p = 0.039$, see Fig. 6.10(3)). Finally, the x-position also affects the maximal rotation angle of the bottom joint in rotation around the y-axis (*max_y* at *TBJ:* $F_{5,4273} = 4.203$ $p > 0.001$; Tukey: 98 mm vs. 186 mm: $p = 0.007$; 98 mm vs. 208 mm: $p = 0.008$, see Fig. 6.10(4)).

In summary, the greatest influence of target position on joint angles was indicated for the bottom joint (TBJ) of the right hand. In general, the thumb was moved less and bended less at the x-positions that required least target selection time

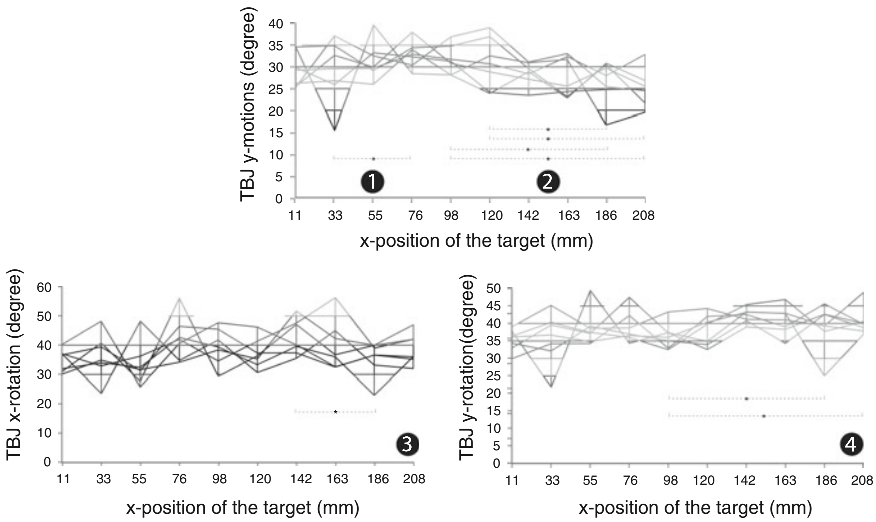


Fig. 6.10 Significant different (*) thumb motions and maximal joint rotation per x-position of selected targets

(X = 33/186 mm counted from the left edge). Motions are shown in Fig. 6.10(1), (2); and joint rotation is presented in Fig. 6.10(3), (4).

6.5.2 Back-of-Device Pointing

Similar to pointing performance on the front sided touchscreen, ANOVAs were conducted for analyzing back-of-device pointing. The motion of the index finger joints (*DIP*, *PIP*, and *MCP*, Fig. 6.9) while pointing at certain x- and y-positions on the back of the device was measured as *range_x*. The amount each joint was rotated most while selecting a target was recorded as *max_x*.

The average of maximal joint rotation (*max_x*) of the index finger while pointing at different target positions on the back of the device differed significantly for the right hand for motions around the x-axis of the middle joint (*PIP*) when pointing at different x-positions ($F_{5,2681} = 2.410$ $p = 0.025$); but no significant result was found in a post-hoc Tukey test ($p > 0.05$). Figure 6.10 shows the maximal rotation angle for the x- and y-positions. However, no significant difference was found in dependence of the x- or y-position; the diagram shows that the joint is rotated most at the vertical center (Y = 64 mm) of the outer x-positions (X = 11/208 mm). These positions (which this 3D analysis was aimed to better understand) require longer selection times than the ones that are located a bit further in the center (X = 33/186 mm).

6.6 Discussion of 3D Results

Although, the tendency that the area very close to the start button requires more manual effort than the optimal target position cannot be shown through significance tests, this phenomenon that we found through analyzing the 2D data becomes visible by descriptive diagrams that show the effort and maximal rotation per joint over the x- and y-position of the device, as shown in Figs. 6.10 and 6.11.

The data of the kinematic hand model was analyzed to explain the unexpected longer selection times of targets that are located very close to the vertical device edges compared to those a bit further away. It was suggested that very close targets may need more time than those a bit further away as the digit that is selecting that target may need to rotate its angles up to the limit that is possible which may result in worse performance. Moreover, the amount of movement were analyzed as pointing time is expected to increase with larger distance (Fitts 1954), and larger distance requires more movements.

Joints allow rotations up to different maximal angles, as shown in Fig. 6.12. The assumption of the previous analysis is that pointing takes longer if the target position requires a digit to be bent in a way that stresses its joints by approaching the rotation limit. The rotation limits of the thumb joints are, according to Vardy (1998) and Hrabia et al. (2013), *max_x* = 90° for the *TDIPI* joint, *max_x* = 85° for

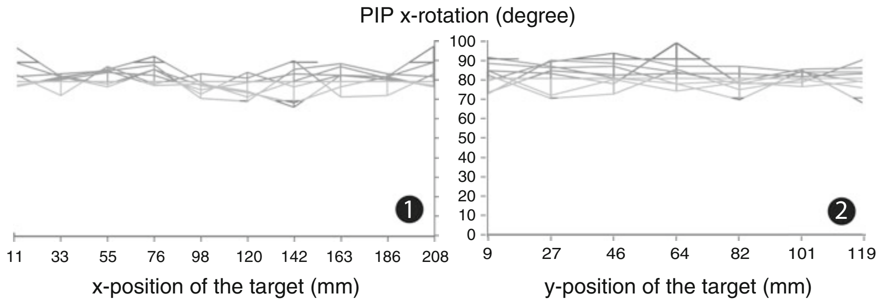
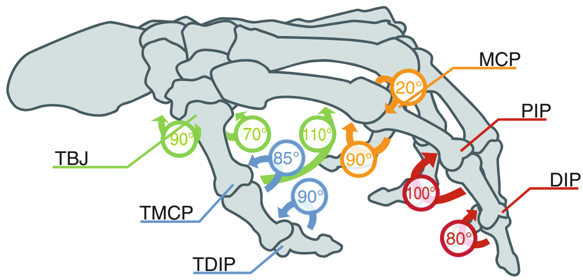


Fig. 6.11 Motions (*1*) and maximal joint rotation (*2*) of the index finger per x-position of selected targets

Fig. 6.12 Maximal joint rotation of digit joints



the *TMCP* joint as well as $max\_x = 110°$, $max\_y = 70°$, and $max\_z = 90°$ for the *TBJ* joint.

Even though the maximal rotation angles per x- and y-positions do not differ significantly for back-of-device pointing; it has been shows that for the very outer positions (X = 11/208 mm, Fig. 6.11) the index finger has to be bent to its biomechanical limitation of about 100°, which is shown in Fig. 6.12. Thus, it has been shown that the index finger's middle (*PIP*) joint is rotated until its limit at those target positions that take longer than targets a bit further away. This is a novel finding related to tablet interaction as usually a Fitts' Law like approach would predict shorter selection times for targets closer to the start position.

However, the joint rotation of the thumb does not reach an angle that is close to the limit (Fig. 6.10); again targets that are a bit further away than the positions close to the edge require fewer rotations of the *TBJ* joint. Furthermore, the physical effort measured in amount of motions is less for these targets (X = 33/186 mm) than for the closer ones (X = 11/208 mm).

One may question why the center regions do not show any difference to the other positions as these were indicated to take longest when analyzing the 2D data (Figs. 6.5, 6.6, 6.7 and 6.8). For reaching the center areas the entire hand had to be moved as digit motions alone cannot access the center of a tablet. The shift from relying rather on digit movements for closer target selection toward moving the whole hand for targets that are further away refers to the kinematic chain model (McCarthy 1990).

In summary, the rotation maximum as well as the amount of motion during target acquisition is influenced significantly through the target position, whereby the thumb shows significantly different movements and configurations in the bottom joint regarding the x- and y-axis of this joint, but never for the z-axis. The effects of the target position on the kinematic model of the thumb were shown to be significant between the center and outermost positions; while the index finger show the tendency to be bent most when targeting very close to the edge.

Thus, the finding of the 2D data is that targets at the optimal position can be selected faster than closer ones; it could not be shown through ANOVAs. But this effect is also not large within the 2D data, and the differences between the outer and the center positions are equally well visible in both the 2D as well as in the 3D data. Therefore, as done with the 2D data, the characteristics of the optimal target position is visualized by diagrams plotting the average maximal rotated joint angles as well as amount of motion over the x-positions at the device, as shown in Figs. 6.10 and 6.11. While the joints have to move more for touchscreen pointing or are stressed at the outer x-positions for back-of-device pointing, an optimal position about 59 mm from the vertical frame edges and 84 mm from the upper device edge (including the frame) could be indicated to be the ergonomically optimum. For touchscreen interaction, this corresponds to the position where the thumb is roughly hovering when holding the device relaxed, as shown in Fig. 6.13. For back-of-device interaction, the fingers are placed roughly there to hold the device.

However, these findings are similar to one-handed thumb interaction, where the thumb performs best when it is not flexed nor fully extended, but in a relaxed

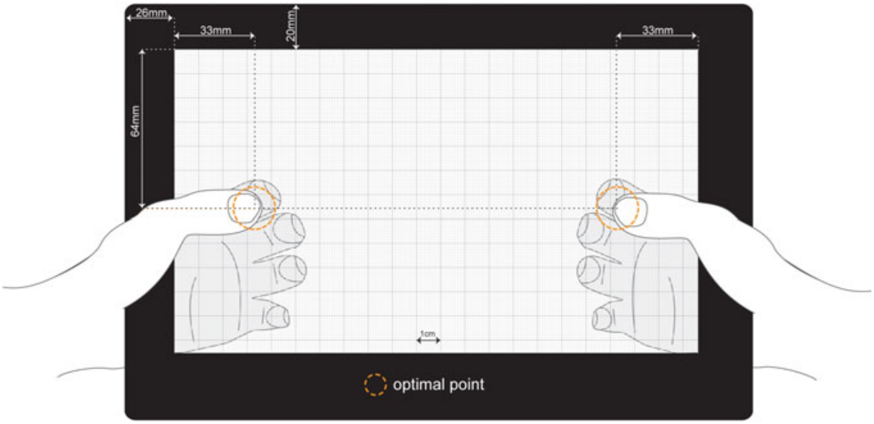


Fig. 6.13 The areas where the thumb (or for back-of-device interaction the fingers) hovering are predestinated for touch-based interaction. These are ergonomic optimal points that require the least target selection time

position (Park and Han 2010; Trudeau et al. 2012), this experiment showed that a similar phenomenon was found for the index finger for back-of-device interaction. Furthermore, the two-handed grip allows relaxing one hand quite a bit for accessing the middle of the tablet, as shown in Figs. 6.7 and 6.8. Accessing these areas would not be possible for one-handed interactions and it does not even stress the joints significantly, as the entire angle motion does not increase dramatically (Figs. 6.10 and 6.11). This can be explained by the kinematic chain model (McCarthy 1990), which assumes that the next joint, which is the wrist, makes more motor work when the digits reach their limit. This phenomenon does not occur in one-handed phone interaction and is thus a true contribution in understanding ergonomics in pointing with the hand that holds a tablet. Thus, due to the two-handed grasp when holding a tablet in the proposed way, the access area of a hand-held device increases for interactions that are performed with the grasping hand.

6.7 Design Guidelines

In the following part, conclusions are drawn that propose design guidelines for pointing on both tablet sides while holding it with two hands. However, Trudeau et al. (2012) proposed to place widgets at locations that are well reachable with the thumb; here guidelines are recommended that do not constrain the interaction area to well accessible locations but rather aim to address the challenge of pointing targets at the entire surface on the front and on the back of the device. Furthermore, the ergonomically optimal point for direct touch pointing at the location where the digits naturally are while holding the device will be the base for the guidelines.

Considering ergonomic optimal points: Locations where the digits are hovering while holding the device are recommended to place GUI components controlled by direct touch. On average these optimal points are located at about 59 mm from the vertical frame edge and 84 mm from the upper device edge (including the frame). Users' hands differ in size and the device grasp differ between users and also between situations for the same user. Thus, a dynamic definition of the ergonomic optimal point may be appropriate when placing icons and widgets in the layout.

Pointing techniques: If it is desired to reach the entire tablet surface on the front and on the back of the device, direct touch has several ergonomic shortcomings. Targets that are further away from the area where the hands are holding the device are hard to reach directly. Moreover, areas that are very close to the edge that is grasped are inconvenient to point at. Thus, indirect touch (relative pointing) should be used instead of direct touch for pointing. Combining the ergonomically optimal point with a relative pointing technique allows overcoming the shortcomings of the direct touch technique for distance pointing on touch-sensitive surfaces.

Dynamic GUI components: Components should be re-thought in order to utilize the good reachability at the vertically outer sides. For instance, virtual keyboards should be vertically split into two parts for two-handed tablet interaction, whereby the right part is displayed where the right hand is grasping the device and the left part where the left hand is holding it. With that guideline, an empirical evidence for a hybrid keyboard design that combines both, the dynamic to the grasp re-adjusting *iGrasp* keyboard (Cheng et al. 2013) and the split keyboard of Oulasvirta et al. (2013) is provided.

6.8 Conclusion and Contribution

6.8.1 Conclusion

This chapter describes work towards considering hand posture and articulation in target acquisition tasks using the thumb for touchscreen pointing and the index finger for back-of-device pointing with tablets. Design features of mobile computing technology such as device size and key location may affect thumb motor performance in touchscreen performance as well as the index finger performance for back-of-device interaction when the device is held with both hands. Empirical observations on biomechanical factors affecting target acquisition performance are made using a contact-based tracking apparatus as well as a hand model glove in a target acquisition task. This allowed observations on biomechanical effects on user performance. Ergonomic optimal points for touch-locations are identified for each hand that grips the device and for both device sides. Finally, pointing design guidelines are formulated that rely on ergonomic optimal points to overcome the shortcomings of the direct touch technique for distance pointing on touch-sensitive surfaces that are grasped, such as tablets that are held with both hands. Finally, indirect mapping between the touching digit and the selection area is recommended to select targets that are hard to reach.

6.8.2 Contribution

This chapter provides the following contribution:

- Target acquisition performance is analyzed with respect to target size, target position, device side, interacting hand, and error rate.
- Heatmaps that present target acquisition time for the interaction areas on both, the front and the back of tablets devices are provided.
- Insights in hand postures while selecting targets at specific positions are presented.
- Guidelines for designing pointing techniques for tablets that are held with both hands are provided.
- The main results of experiment presented in this chapter (excluding some of the data presentation, e.g. Tables 6.1 and 6.2) are submitted under Wolf et al. (2014c). Insights in biomechanics of the hand (intra-finger angular dependencies) using the same hand model software as in this experiment are published in Hrabia et al. (2013). This publication was as result of a Master's thesis that was supervised by the author in collaboration with Matthias Wilhelm (Dai Labor Berlin).

Chapter 7
Pointing on Tablets with Grasping Hands

While a large body of work has investigated touch interaction on smaller devices, is little empirical research has been carried out on touch-based pointing while holding the device with both hands. To understand touch-based interactions using tablet devices, an experiment was conducted to compare four pointing techniques on both the front and back of the devices while it was held in landscape format. Direct touch is compared with the following alternatives for selecting targets, relative pointing on a touchPad, an inverse cursor, and a miniature interaction area. The presented study shows that among the indirect pointing techniques, the miniaturized interaction area is significantly faster and received the best subjective ratings. In concluded design guidelines a miniaturized interaction area is recommended to be a viable alternative to direct touch especially on the backside of tablet devices.

7.1 Pointing Techniques

Indeed one of the most common ways to hold the device is using a two-handed grip (particularly if used in landscape format). Grasp-based pointing on tablets can cause ergonomic problems. Due to the large size of tablets, the thumbs and fingers are sometimes unable to reach the center of the display, while the device is being held (Odell and Chandrasekaran 2012). Therefore, direct touch, which is the most common pointing technique for touchscreens, may be not the most appropriated one for tablet devices, which has been shown in Chap. 5.

The technology company Apple filed a patent on back-of-device interaction in 2006 (Kerr et al. 2006), and Wigdor et al. (2007) demonstrated in 2007 how back-of-device interaction when using a tablet-sized device solves the *fat-finger problem* (Siek et al. 2005). Since the release of the Motorola CHARM in 2010 and the Sony Vita in 2012, mobile devices with a touch-sensitive back are commercially available. It can be expected that touchpads will soon be embedded in the back of many devices. Previous research did not address pointing through back-of-device interaction on tablet devices and consequently, corresponding design guidelines are not

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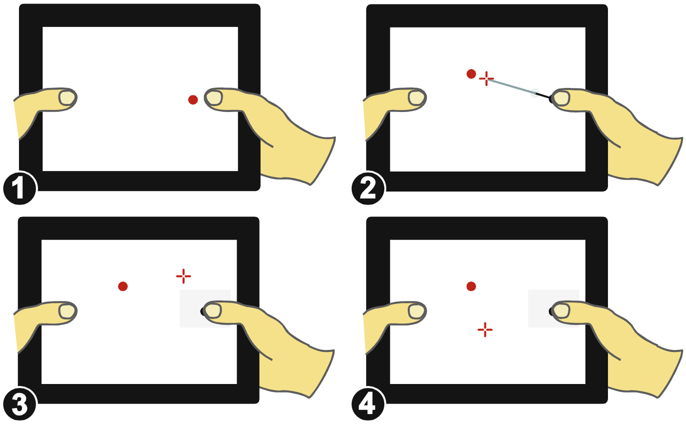


Fig. 7.1 This chapter investigates pointing techniques that are performed without losing the tablet grip: *(1)* direct touch, *(2)* inverse cursor, *(3)* touchPad *(4)* miniature area

available. Thus, this chapter considers both, pointing on touchscreens as well as on touchpads built in the back of the device.

Pointing performance with grasping hands is constrained by parameters, such as reachability and joint flexion of the pointing digit. To understand touch-based interaction using tablet devices, an experiment was conducted that compares four pointing techniques on the front and on the backside of tablet devices while the device is being held in landscape format. In this chapter direct touch is compared with selecting targets using a touchpad, an inverse cursor, and a miniature interaction area.

Previous work proposed the following four categories of touch-based pointing techniques: direct pointing, inverse direct pointing, relative pointing, and remote direct pointing. In the experiment presented here, four pointing techniques are evaluated (Fig. 7.1); and each of them represents one of the categories. Direct pointing is represented through *direct touch* (1). The *inverse cursor* (2) stands for the direct inverse pointing techniques. The *touchPad* (3) allows relative pointing; and the *miniature area* (4) enables direct remote pointing using a miniaturized display that represented the entire interaction area of the tablet.

7.1.1 Direct Touch

Direct touch is the common pointing technique for touchscreen interactions. The digit is directly touching the location where a target is displayed. If the direct touch is performed with the hands that hold a tablet in a symmetric bimanual grip, the thumb can execute direct touch on the front of the device and a finger does it on the back side. Direct touch is known to cause occlusion problems with touchscreens.

This problem is addressed through back-of-device pointing proposed by Wigdor et al. (2007). Moreover, direct touch can make it difficult to access the center of tablets that are held with both hands (Odell and Chandrasekaran 2012).

7.1.2 Inverse Cursor

The inverse cursor technique refers to *MagStick* (Roudaut et al. 2008) and *Large Touch* (Kim et al. 2012), which were developed for one-handed phone interactions. Similar to both approaches, the *inverse cursor* is controlled by setting an initial anchor point through a touch; and a drag gesture from that initial touch point pulls a cursor in the opposite direction. While the distance the cursor is moved using *MagStick* is similar to the length of the drag gesture; *Large Touch* translates the drag gesture to a larger cursor movement to overcome accessibility problems in one-handed phone interaction. The amount of movement of the *inverse cursor* is adaptive to allow for the entire interaction area to be always accessible when interacting with the hand that grasps the device. The cursor motion depends on the position of the start of the drag gesture. As the cursor movement is defined by an inverse digit movement, dragging the digit to the very outer touchscreen boarder will move the cursor to the touchscreen's very outer opposite edge. This ensures that every screen position is accessible.

7.1.3 TouchPad

The *touchPad* technique is a virtual reference to physical touchpads that are commonly built in laptop computers. Researchers found that there are many ways to hold a tablet device (Oulasvirta et al. 2013; Wagner et al. 2012); and Cheng et al. (2013) proposed placing GUI components (such as virtual keyboards) where people grasp a tablet. Accordingly, the *touchPad* evaluated here appears after an initial touch. A drag gesture on the *touchPad* moves a cursor relatively. For target acquisition using the *touchPad*, several drag gestures may be required to point on a target. Thus, a release cannot be used to confirm a target acquisition to finish the selection. A tap gesture has been chosen as confirmation for target selection. *TouchPad* is the only relative pointing technique in the presented experiment. Relative pointing is known to be slower but more precise than absolute pointing techniques, such as direct touch (Cockburn et al. 2012; Hassan et al. 2012).

7.1.4 Miniature Area

The principle of the *miniature area* proposed here is to provide a miniature representation of the entire screen that is accessible using the grasping hand. The approach is inspired by *ThumbSpace* (Karlson and Bederson 2007), the *Sliding-screen* (Kim et al. 2012), and the *ARC-Pad* (McCallum and Irani 2009). While the *ARC-Pad* uses a mobile phone as a physical one-to-one representation of a large display; the proposed *miniature area* is a virtual miniature one-to-one representation of the tablet's interaction area. Unlike *ThumbSpace* and *Sliding-screen*, which require defining the interaction area size with a drag gesture; *miniature area* does not require an extra interaction step to size the interaction area. The miniature display representation is pre-defined in size and is dynamically placed through a touch gesture. That is similar to the adaptive placement of the *touchPad* and ensures that the *miniature area* is always well accessible aiming for faster interaction. Unlike the *touchPad* that requires a tap gesture to confirm a target selection process, the *miniature area* in more immediate. Target acquisition is realized through touching the *miniature area* at the position that is mapped to the corresponding target position on the tablet's display. The position on the large screen that a touch on the *miniature area* is referring to is visualized through a cursor. Drag gestures allow for moving a cursor. A touch release confirms the target acquisition and ends the selection process.

7.2 Method

To provide foundational knowledge about grasp-based pointing on tablets, and to help designers to understand the human factors, four pointing techniques are compared in a controlled experiment. The pointing techniques are evaluated to determine their performance as well as perceived effort and usability. Performance provides insights in target accessibility and selection time. Effort and usability help understanding which pointing technique is preferred for what reason.

7.2.1 Design

The presented study had a $4 \times 2 \times 2 \times 3$ within subject design with the independent variables *pointing technique* (direct touch, inverse cursor, touchPad, miniature area), *hand* (right, left), *device side* (front-, back-of-device), and *target size* (5, 7, 10 mm). The targets were arranged in a 10×7 grid that was equally distributed over the touchscreen, excluding 2 positions of "start" buttons at the vertical center of both most left and right outer x-positions. One target per size appeared per target position in each condition. Thus, 204 targets had to be selected (or rejected if not accessible) per condition, resulting in 3,264 targets per participant. The dependent variables were *target selection time*, *selection effectiveness*, *perceived effort*, and *usability*.

7.2.2 Task

For each pointing technique, the participants were asked to select targets that appeared after pressing a “start” button as fast and precise as possible. For target selection at the front, the thumb was used. For back-of-device target selection, the participants could use any finger.

7.2.3 Apparatus

A tablet sandwich was used to present the experimental task and to record logfiles.[1] It consisted of two tablet devices glued with their rear sides together and connected via Bluetooth (inspired by Shen et al. (2009)). This allowed for sensing touch events on the back of the apparatus and to update the GUI of the device at the front accordingly. The resolution of the screen was 1280 × 742 pixels (without bottom menu bar) with a size of 21.7 cm × 13.6 cm.

7.2.4 Measurements

Touch events (for each *pointing technique, hand, device side, target size*, and *target position*) were recorded in logfiles. Perceived effort (for each *pointing technique* and each *device side*) was measured using the SEA scale (Zijlstra 1993), because it is known to be very sensitive with small sample sizes (Sauro and Dumas 2009). The usability of each pointing technique was recorded using the AttrakDiff questionnaire (Hassenzahl and Monk 2010).

7.2.5 Procedure

14 right-handed participants (6 females) with different academic backgrounds, such as computer science, history of art, and media design and an average age of

[1] The apparatus was built by Niels Henze who co-authored the paper corresponding to this chapter, which will be published at MobileHCI 2014.

29.6 years (SD = 4.3) were recruited to participate in the study. All participants were familiar with touchscreens, but none had experienced back-of-device interaction before. During the tasks, the participants were holding the apparatus in landscape format with two hands in a symmetric grip. Each pointing technique was used on both device sides using one hand after the other. If a target by any reason was perceived to be not easily selectable, the participants were asked to press a "cancel" button. The order of the 16 conditions was randomized. Each participant was asked to perform the tasks using each condition after a short training phase. After completing a condition, the participants filled the SEA and the AttrakDiff questionnaires. The experiment was split into two sessions. Each session lasted between 1.5 and 2 h. When all conditions were completed, a demographic questionnaire was filled.

7.3 Results

The results contain effectiveness (measured as percentage of targets that could successfully be selected), efficiency (measured as task completion time), selection time per target position, number of attempts to select a target, perceived effort, and usability.

7.3.1 *Effectiveness*

Effectiveness represents the target accessibility for the different pointing techniques. If the participants were not able to select a target, for instance because they could not reach it, they could skip that task with a "cancel" button. The cancelled selection tasks per pointing technique are presented in Table 7.1.

While the target accessibility for *inverse cursor*, *touchPad*, and *miniature area* was 100 % on the front side and above 98 % on the back of the device. Pointing with *direct touch* was cancelled in more than half of the cases. As it is expected,

Table 7.1 Cancelled selections tasks per pointing technique

Pointing technique	Direct touch	Inverse cursor	TouchPad	Miniature area
	Front of the device (%)			
Right hand	50.95	0.00	0.00	0.00
Left hand	51.65	0.00	0.00	0.00
	Back of the device (%)			
Right hand	52.71	0.00	0.00	0.09
Left hand	54.34	0.17	0.04	1.57

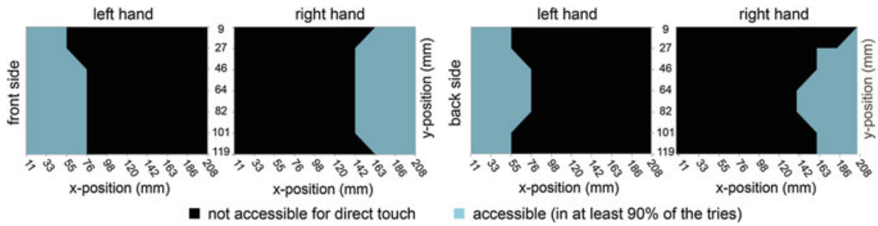


Fig. 7.2 Locations of the targets that are accessible using direct touch

targets that are further away from the grasping hand are not reachable via direct touch. The target positions that were accessible in at least 90 % of the attempts cover 37 % of the front sided interaction area for each hand as well as 34 % of the back of the tablet using the left hand and 30 % using the right hand, as shown in Fig. 7.2.

7.3.2 *Efficiency*

Efficiency is measured as *target selection time* for the targets that were successfully selected. The selection tasks that were cancelled are not considered in this analysis. 528 of the 45.696 tasks that were more than three standard deviations from the mean and took longer than 8.644 s were removed (Tukey 1977). The average selection times (Mean) and the standard deviations (SD) are presented in Table 7.2.

A Kolmogorov-Smirnov-Test shows that our data is normally distributed. Mauchly's test indicated that the assumption of sphericity has been violated for the interaction effects *technique* * *hand* ($p < 0.001$). Therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity for the respective tests.

Table 7.2 Mean and SD for target selection time in seconds

	Direct touch (s)	Inverse cursor (s)	Touch-Pad (s)	Miniature area (s)
Mean	1.28	2.93	2.53	1.97
SD	0.74	1.29	0.92	0.87
	Device side		Hand	
	Front (s)	*Back (s)*	Left (s)	Right (s)
Mean	2.06	2.57	2.40	2.22
SD	1.06	1.17	1.15	1.13
	Target size			
	5 mm (s)	7 mm (s)	10 mm (s)	
Mean	2.51	2.30	2.13	
SD	1.24	1.13	1.03	

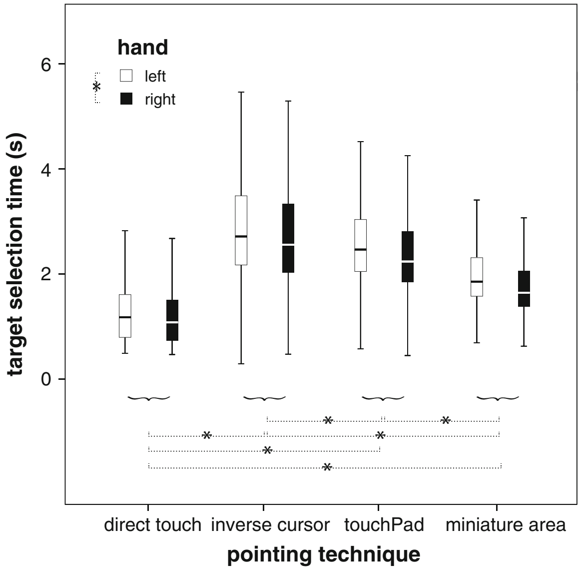


Fig. 7.3 Selection times over pointing technique per hand and sign. differences (*)

There was a significant main effect of *pointing technique* on the task completion time ($F_{3,36} = 124.24$, $p < 0.001$). Bonferroni corrected pair-wise t-tests revealed significant differences between the four *pointing techniques* ($p = 0.007$ for *inverse cursor* vs. *touchPad* and $p < 0.001$ for all other comparisons, see Fig. 7.3). Similarly, *hand* ($F_{1,12} = 20.77$, $p = 0.001$), *device side* ($F_{1,12} = 60.64$, $p < 0.001$, Fig. 7.4), and *target size* ($F_{2,24} = 167.80$, $p < 0.001$) had a significant effect on the task completion time. Bonferroni corrected pair-wise t-tests revealed significant differences between the three *target sizes* ($p < 0.001$, see Fig. 7.5). We found

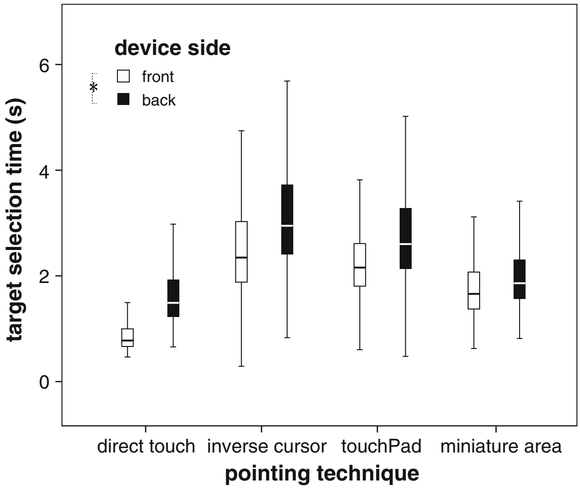


Fig. 7.4 Selection times over pointing techniques per device side

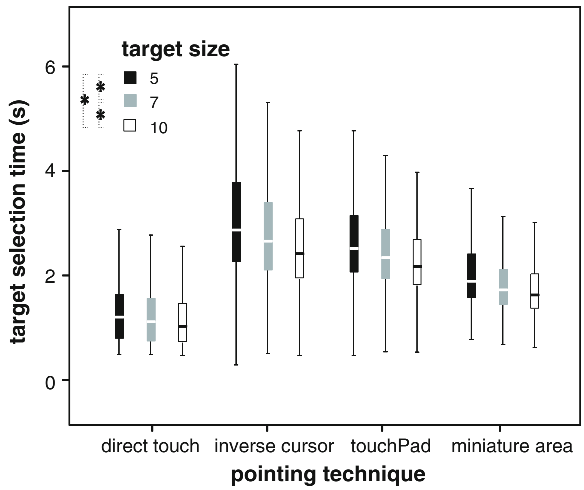


Fig. 7.5 Selection times over pointing techniques per target size

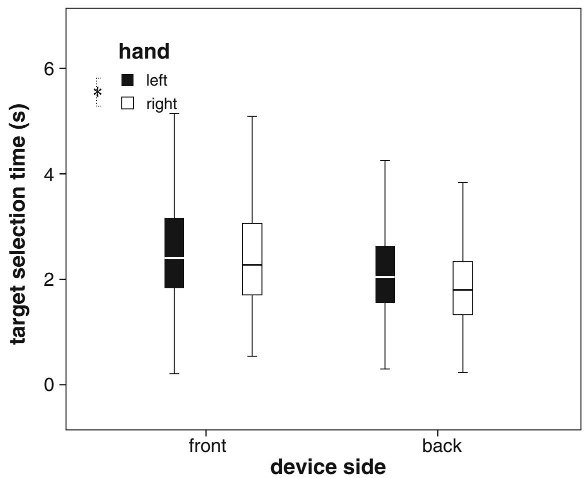


Fig. 7.6 Selection times over device side per hand

interaction effects for *technique* * *device side* ($F_{3,36} = 10.33$, $p < 0.001$), *hand* * *device side* ($F_{1,12} = 6.88$, $p = 0.022$, Fig. 7.6), and *technique* * *target size* ($F_{6,72} = 21.22$, $p < 0.001$). In contrast, there were neither significant interaction effects for *technique* * *hand* ($F_{1.27,15.19} = 0.76$, $p = 0.43$), *hand* * *target size* ($F_{2,24} = 0.15$, I = 0.87), nor for *device side* * *target size* ($F_{2,24} = 2.98$, $p = 0.07$).

7.3.3 Selection Time Per Target Position

Selection time for each *target position* was calculated if the target was at least successfully selected in at least 90 % of the *attempts*. Otherwise the *target position* was identified to be not accessible. The median time needed to select a target at a certain position is presented in Fig. 7.7. *Direct touch* just allows for accessing targets that are located close to the hand that is selecting it. The other three techniques allow accessing the entire interaction area on both, the front and the back of the device. As shown in Fig. 7.3; the *inverse cursor* has the lowest performance. Selection time increases the further the target is from the selecting hand for the *inverse cursor* and the *touchPad* technique. The *miniature area* results in an almost constant time across the screen and also in the highest selection performance over the entire interaction area on both *device sides*.

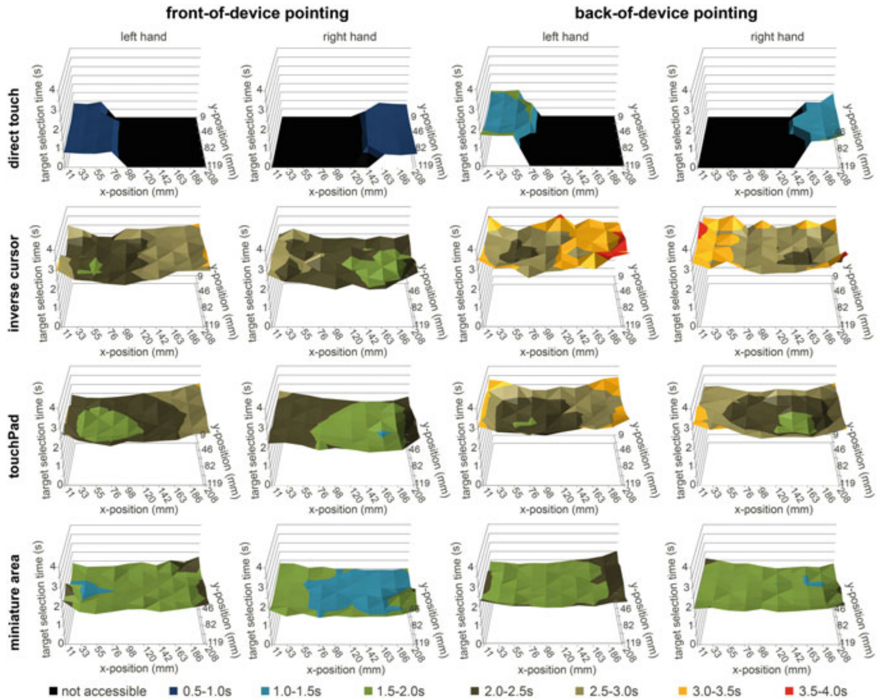


Fig. 7.7 Target selection time (median) for each target position at the front and the back of a tablet (counted in mm from the *top left*). If the target could not be selected in 90 % of the attempts in a certain position, this position is labelled as not accessible

Table 7.3 Mean and SD for number of attempts to select a target

	Direct touch	Inverse cursor	TouchPad	Miniature area
Mean	1.2	1.2	3.1	1.1
SD	0.6	0.6	1.1	0.4
	Device side		Hand	
	Front	Back	Left	Right
Mean	1.7	1.7	1.7	1.7
SD	1.2	1.2	1.2	1.2
	Target size			
	5 mm		7 mm	10 mm
Mean	1.8		1.7	1.7
SD	1.2		1.2	1.1

7.3.4 Number of Attempts Per Target Selection

The number of *attempts* participants needed to successfully select a target was counted. Cancelled attempts were ignored for this calculation. All tasks that were more than three standard deviations from the mean and took more than 10.4 attempts were removed (Tukey 1977). The average number of attempts (Mean) and the standard deviations (SD) for each pointing technique, device side, hand, and target size are presented in Table 7.3.

Again, a Kolmogorov-Smirnov-Test shows that our data is normally distributed, and Mauchly's test indicated that the assumption of sphericity has been violated for the main effect technique ($p < 0.001$) as well as for the interaction effects *technique * hand* ($p < 0.001$), and *technique * device side* ($p = 0.001$).Therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity for the respective tests.

There was a significant main effect of the *pointing technique* on the number of attempts participants needed to select a target ($F_{1.07,12.87} = 175.89$, $p < 0.001$. Bonferroni corrected pair-wise t-tests revealed significant differences between *inverse cursor* and *touchPad* ($p < 0.001$), *direct touch* and *touchPad* ($p < 0.001$), *direct touch* and *miniature area* ($p = 0.002$), as well as *touchPad* and *miniature area* ($p < 0.001$), see Fig. 7.8. There were no significant main effects for *hand* ($F_{1,12} = 0.001$, $p = 0.97$) or *device side* ($F_{1,12} = 0.03$, $p = 0.87$). *Target size* ($F_{2,24} = 33.17$, $p < 0.001$) had a significant effect on the number of attempts. Bonferroni corrected pair-wise t-tests revealed significant differences between all *target sizes* ($p = 0.047$ for 5 mm vs. 7 mm, $p < 0.001$ for 5 mm vs. 10 mm, and $p = 0.001$ for 7 mm vs. 10 mm). We found significant interaction effects *for technique * target size* ($F_{6,72} = 11.14$, $p < 0.001$) and *device side * target size* ($F_{2,24} = 8.93$, $p < 0.001$). There were neither significant interaction effects for *technique * hand* ($F_{1.53,18.35} = 0.52$, $p = 0.07$), *technique * device side* ($F_{1.91,22.89} = 2.73$, $p = 0.09$, Fig. 7.9), *hand * device side* ($F_{1,12} = 0.13$, $p = 0.91$), nor for *hand * target size* ($F_{2,24} = 0.26$, $p = 0.97$).

Fig. 7.8 Number of attempts over pointing technique per hand and sign. differences (*)

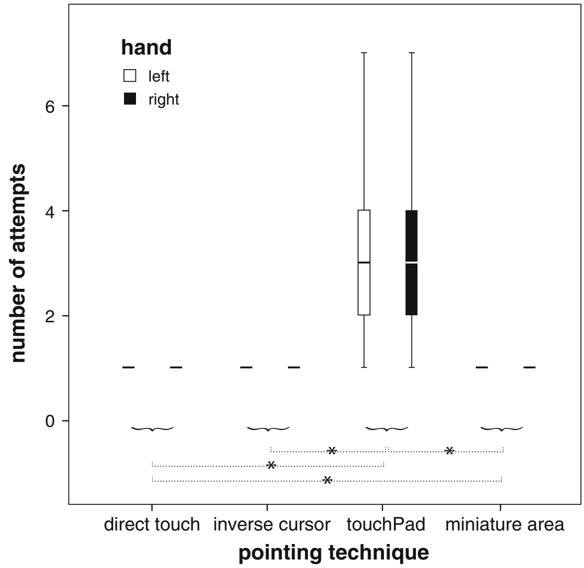
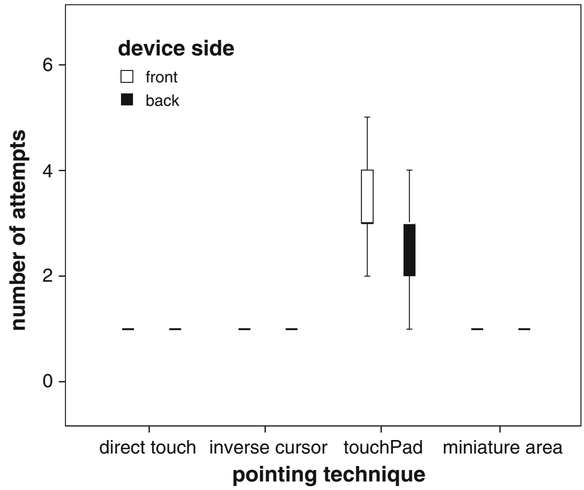


Fig. 7.9 Number of attempts over pointing techniques per device side



7.3.5 Perceived Effort

The perceived effort was measured using the *SEA* on a scale from 0 (no effort) to 220 (high effort). The average perceived effort (Mean) and the standard deviations (SD) as well as the according effort description are presented in Table 7.4.

A repeated measure ANOVA yielded a significant different perceived effort for *pointing technique* ($F_{3,80} = 7.2$, $p < 0.001$). For *device side* it was shown that

Table 7.4 Perceived effort with Mean, SD, and description for device side per pointing technique

Pointing technique	Direct touch		Inverse cursor		TouchPad		Miniature area	
Device side	Front	Back	Front	Back	Front	Back	Front	Back
Mean	59.9	102.7	101.4	108.2	59.1	50.6	40.8	57.6
SD	53.4	63.9	64.3	78.7	36.2	35.2	23.8	52.1
Description	A bit hard	Fairly hard	Fairly hard	Pretty hard	A bit hard	A bit hard	A bit hard	A bit hard

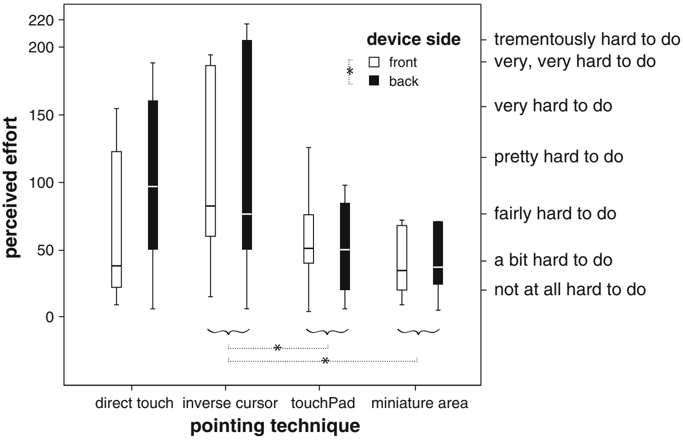


Fig. 7.10 Perceived effort over pointing techniques per device side

interacting on the front was perceived significantly easier ($F_{1,92} = 7.9$, $p = 0.006$). Moreover, an interaction effect for *pointing technique* * *device side* has been found ($F_{3,81} = 3.1$, $p = 0.030$).

While Bonferroni-corrected pairwise comparisons (Fig. 7.10) showed that the *inverse cursor* technique was perceived to be significantly harder than the *touchPad* ($p = 0.021$) as well as than the *miniature area* ($p < 0.001$), no significant difference was found between *direct touch* and any other technique (*direct touch* vs. *inverse cursor*: $p = 1.000$, *direct touch* vs. *touchPad*: $p = 0.221$, and *direct touch* vs. *miniature area*: $p = 0.336$). Furthermore, no significant difference between the *touchPad* and the *miniature area* was found ($p = 1.000$).

7.3.6 Usability

The four sub-scales of the AttrakDiff questionnaire, which describe usability, are pragmatic qualities, the hedonic quality of identification, the hedonic quality of stimulation, and global attractiveness. All four scales have as minimum 1 and as

Table 7.5 Mean values and SD for the AttrakDiff sub-scales

	Direct touch	Inverse cursor	TouchPad	Miniature area
	Pragmatic quality			
Mean	4.8	3.9	5.2	5.2
SD	0.2	0.4	0.2	0.3
	Hedonic quality: identification			
Mean	4.1	4.4	4.2	4.7
SD	0.2	0.2	0.2	0.2
	Hedonic quality: stimulation			
Mean	4.4	4.2	4.4	4.4
SD	0.3	0.3	0.3	0.3
	Global attractiveness			
Mean	4.6	3.8	4.9	5.2
SD	0.3	0.3	0.2	0.3
	Front-of-device		Back-of-device	
	Pragmatic quality			
Mean	5.0		4.6	
SD	0.2		0.3	
	Hedonic quality: identification			
Mean	4.3		4.4	
SD	0.2		0.2	
	Hedonic quality: stimulation			
Mean	4.1		4.5	
SD	0.3		0.2	
	Global attractiveness			
Mean	4.9		4.4	
SD	0.2		0.3	

maximum 7, while high values refer to high qualities. The average usability qualities (Mean) and the standard deviations (SD) are presented in Table 7.5.

A MANOVA yielded significantly different ratings per *pointing technique* for the *global attractiveness* and the *pragmatic qualities* (*global attractiveness*: $F_{3,114} = 9.2$, $p < 0.001$, *pragmatic quality*: $F_{3,114} = 10.2$, $p < 0.001$). Both hedonic qualities, *identification* and *stimulation* were not rated differently (*identification*: $F_{3,114} = 2.5$, $p = 0.071$, *stimulation*: $F_{3,144} = 1.8$, $p = 0.155$). *Attractiveness* and the *pragmatic qualities* were differently rated in dependence of *device* (*global attractiveness*: $F_{1,10} = 6.7$, $p = 0.023$, *pragmatic quality*: $F_{1,10} = 8.9$, $p = 0.011$), while *device* had no influence on the *hedonic qualities* (*identification*: $F_{3,114} = 1.4$, $p = 0.517$, *stimulation*: $F_{3,144} = 4.5$, $p = 0.054$). No interaction effect was found between the *pointing techniques * AttrakDiff scales* (*pointing technique * global attractiveness*: $F_{3,114} = 1.3$, $p = 0.291$, *pointing technique * pragmatic quality*: $F_{3,114} = 1.4$, $p = 0.268$, *pointing technique * stimulation*: $F_{3,144} = 2.2$, $p = 0.103$, *pointing technique * identification*: $F_{3,114} = 2.0$, $p = 0.128$).

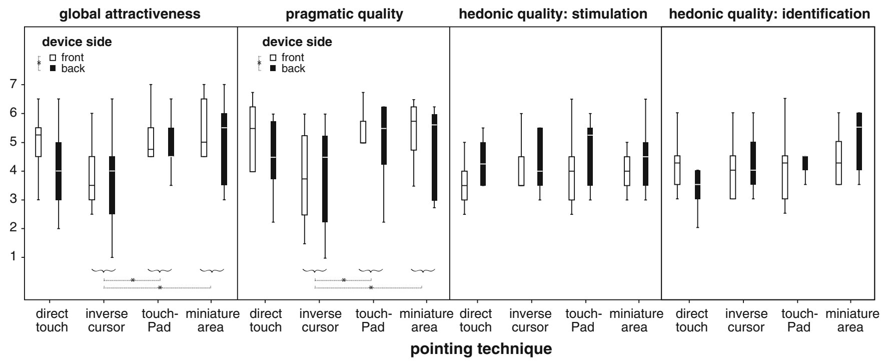


Fig. 7.11 Usability scales: global attractiveness, pragmatic quality, hedonic quality stimulation, hedonic quality identification to rate the four pointing techniques from 1 = low rating to 7 = high rating

For *attractiveness*, Bonferroni-corrected pairwise comparisons (Fig. 7.11) showed that the *inverse cursor* technique received significantly lower ratings than the *miniature area* ($p = 0.003$) and the *touchPad* ($p = 0.006$). According *pragmatic qualities*, Bonferroni corrected post-hoc tests showed again that the *inverse cursor* was rated worse than the *miniature area* ($p < 0.001$) as well as than the *touchPad* ($p = 0.002$).

7.3.7 Comments

During the experiment, participants gave additional comments about their experience with the different pointing techniques. Four participants appreciated that targets were not occluded when interacting on the back of the device. Targets are always occluded when pointing via *direct touch* on the front side but also through the other three techniques if the targets were located on bottom positions where the thumb is rested while holding the device. One participant mentioned that a tap was sometimes misinterpreted as a drag using the *touchPad*.

7.4 Discussion

Analysing the collected data indicated that only 37 % of the front and 32 % of the back of tablets is accessible using *direct touch* with one hand. Even with two hands, only 74 % of the front and 64 % of the back were reached. Comparing the direct touch accessibility in this target selection task (Fig. 7.2) with the direct touch accessibility in an undirected task (Fig. 5.7), it can be seen that participants access fewer positions in the undirected task, such as the very upper and the very lower positions. A reason for the better accessibility if targets are required to be selected may be the stronger guidance that is given through the task as well as an increase of spent effort caused by the desire to solve the task.

While *direct touch* is the fastest pointing technique, it has been found that it is only usable for areas at the screen's border. Among the other pointing technique, the *miniature area* is 28.4 % faster than the *touchPad* and 48.7 % faster than the *inverse cursor*. In contrast to the other techniques, the *target selection time* varies little across the screen using the *miniature area*. Looking at the subjective measures of all four techniques, using the *miniature area* resulted in the lowest perceived effort and the highest score on all sub-scales of the AttrakDiff questionnaire even in comparison with *direct touch*.

The presented results are in line with Odell and Chandrasekaran (2012), who found that the center areas of tablet touchscreens are not accessible with *direct touch* as well as with the results of Chaps. 5 and 6, which confirmed this and showed that also for back-of-device interaction the center is hardly accessible for *direct touch*. Moreover, it has been shown that *direct touch* on the back of the device results in the same problem. While Kim et al. (2012) found that their inverse cursor *Large Touch* is as fast as *direct touch* when pointing on mobile phones, the results presented here are contradictory to these but in line with those of Roudaut et al. (2008) who found that *direct touch* is faster than *the inverse cursor* technique using mobile phones. The *miniature areas ThumbSpace* (Karlson and Bederson 2007) and *Sliding-screen* (Kim et al. 2012) implemented for mobile phones were slower than *direct touch*, which is in line with findings presented here using the *miniature area* on the front as well as on the back of tablet devices. Moreover, the *miniature area* proposed here is (similar to the *ARC-Pad*) faster than *relative pointing*, which is represented through the *touchPad* technique in this study. While Hasan et al. (2012) found that *relative pointing* performs better than *direct touch* for one-handed back-of-phone interaction in terms of target selection time as well as accuracy, like Cockburn et al. (2012) it has been found here that *direct touch* is faster than *relative pointing*, using the tested *touchPad* on both the front as well as the back of a tablet. In contrast to the findings of Cockburn et al. (2012) the presented findings do not show an increase in the *number of attempts* for small targets.

In light of the results presented in this chapter, designers of applications for tablet devices currently have two options when arranging interactive controls in a landscape UI. They can either use the whole screen while forcing the user to choose another grip or they can arrange all interactive controls on the 37 % on the front and 32 % on the back of tablets near each vertical screen's border. An indirect pointing technique such as the *miniature area* could offer a third option and make the whole screen easily accessible. As all considered indirect techniques are slower than *direct touch*, a combination of a *miniature area* with *direct touch* is proposed. As the *miniature area* performs equally well on the front as on the back a viable option is to combine *direct touch* on the front with the *miniature area* on the back. This approach has the advantage that a dedicated pointing technique is used on each device side which helps to avoid confusion of the user. Furthermore, the whole screen becomes easily accessible and thus usable for designers.

7.5 Conclusion and Contribution

7.5.1 Conclusion

In this chapter, pointing on tablet devices has been investigated. Four pointing techniques while participants held the device with both hands in landscape format were compared. For this setup, it has been showed that only 74 % on the front and 64 % on the back of tablets can be easily reached using *direct touch*. Among the three alternatives, the *miniature area*, a virtual miniature one-to-one representation of the tablet's interaction area, is the fastest option. As this *miniature area* received the best subjective ratings, even compared to direct touch, it is proposed to combine direct touch on the front of tablet devices with the *miniature area* on the back. This combination would make the whole screen accessible and avoid mixing interaction techniques.

The conducted study focuses on one of the most common ways to hold tablet devices and as participants were comfortably seated the setup mimics the typical usage context. Future work should nonetheless investigate if the results hold true for other postures and situations. Furthermore, the screen size of the used device was 10.1 inch; and future work should investigate additional screen sizes. The fraction of the screen that is easily accessible will become even smaller for larger screens. It would be interesting to investigate if the gained results can be transferred to much larger tabletops where interaction is not restricted by hand size but by arm length.

7.5.2 Contribution

This chapter provides the following contributions:

- Describing the area that is easily accessible using direct touch while the tablet is held in landscape format based on empirical data.
- Comparing four pointing techniques on both sides of tablet devices to show which technique is the best alternative to direct touch.
- Proposing a combination of direct touch on the front and a miniature representation of the tablet's interaction area on the back that makes the whole screen accessible.
- This chapter represents a paper that is submitted under Wolf and Henze (2014).

Chapter 8
Design Guidelines

The main contributions of this thesis as well as of each chapter were concluded in design guidelines. The essence of these guidelines is presented, according to the main research topics of this thesis, in the following three parts: *ergonomic gestures*, *interaction areas*, and *pointing techniques*.

8.1 Ergonomic Gesture Design

As users typically hold tablets in their hands while interacting with them, interaction designers should consider grasp-based interaction when designing for tablet devices. Elementary decisions that have to be made are choosing a *gesture type.* Furthermore, gestures have to be designed adequate to the flexibility of the *digit* that performs the gesture. These topics are described in the following. Afterwards, appropriate parameters for gesture detection algorithms are presented. These parameters serve programmers and developers of APIs and gesture libraries to define gestures, in this case using different thresholds for both, gestures that are executed on the front as well as on the back of a tablet.

8.1.1 Gesture Types

The following gestures have been identified to fit an ergonomic design for grasp-based interaction (see Chap. 3 for further details):

- *Gesture set*: Two gestures types, touch-based and drag-based gestures, are ergonomic for grasp-based interaction. This includes also pressure and swipe gestures, as they are executed similar to touch and drag. These four gestures, tap, press, drag, and swipe, are extremely easy to perform and already known in the domain of touchscreen interaction (Fig. 8.1).

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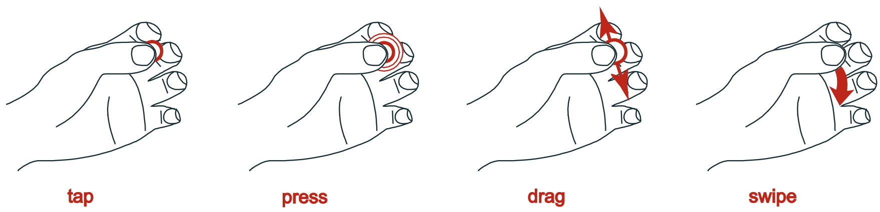

Fig. 8.1 Easily executable gestures while grasping devices/objects

- *Pinch*: The established pinch gesture executed with two digits of a "free" hand on the same surface, which is usually used for zooming on touchscreens, is not an ergonomics gesture for grasp-based interaction. Instead, pinching two fingers against each other, one at the front and one at the back of the device, is feasible, as here the applied forces support the grasp, as shown in Wolf et al. (2012c).

8.1.2 Digits

For grasp-based interaction on a touchscreen the thumb usually performs the gesture; and a finger is used for back-of-device interaction. The digits have different reach that influences how gestures can be executed on the back of the device compared to the front (see Chaps. 3 and 4 for more information).

- *Length*: The length of the digits limits the execution of gestures that requires the digit to reach a specific position, e.g. pointing via direct touch, especially using the little finger. In particular, it has to be ensured for all gestures that require touching a specific location that this location is within reach of the digit.
- *Flexibility*: The digits differ in flexibility. The thumb has the most degrees of freedom and is most flexible (if not necessarily required for grasping). The index and the middle finger are also highly flexible while grasping. The ring finger is not recommended as moving it results in co-motions of the neighbor fingers. Similarly, the little finger cannot easily perform gestures, mainly due to its length.
- *Grasp*: Because four fingers are placed on the back of a device while grasping, the ring and the little finger are needed to hold the device. For grasp-based interaction on the back of the device, the index and the middle finger are appropriate for gesture execution.
- *Most appropriate digits*: Both thumbs can easily execute gestures on the front of a tablet while holding it in both hands. Both, the index finger and the middle finger can release the grasp on the back of tablets for executing gestures. The ring and the little finger are not convenient for grasp-based interaction.

8.1.3 Gesture Definition

The following thresholds are recommended to classify gestures as well as unintended touch events (Midas touch) as shown in Chap. 4.

- *Tap*: A tap gesture is trigged if the time between the digit's touch-down and lift-off is less than 0.5 s and the digit is not moved in any direction. To make the recognition robust and allowing small slips, a movement threshold of 10 pixels (1.5 mm) is recommended.
- *Press*: an action is a press gesture if the time between the digit's touch-down and lift-off is more than 0.5 s.
- *Midas touch*: Midas touch is indicated if a touch event lasts longer than 1.5 s.
- *Drag*: Drag is triggered if a digit is moved more than 10 pixels (1.5 mm) over a time of at least 0.6 s. Longer gesture durations are possible as drag is appropriate for position control that allows for directly manipulating a parameter as long as the digit is moving. A drag that is aimed to be drawn with one stroke without readjusting should not be longer than 320 pixels (49 mm) on the front and not longer than 250 pixels (38 mm) on the back side.
- *Swipe*: an action is triggered as swipe if a digit is moved more than 10 pixels (1.5 mm) in less than 0.5 s. The swipe is performed slower on the back that results in lower friction. Thus, mapping factors onto scroll friction have to be higher for back-of-device swipe gestures.
- *Sliders*: Controlling certain widgets such as sliders or a scrollable list requires a drag gesture. Vertical paths drawn with the thumb and fingers are not straight lines. Thus, for vertical sliders a curved drag path should be considered. Therefore, sliders should be shaped as a bow with the imaginary center point in the palm of the tablet-holding hand. Sliders on the back side should be smaller in size than on the front for both: vertical (front: max. 290 pixels or 44 mm, back: max. 180 pixels or 28 mm) and horizontal sliders (front: max. 220 pixels or 34 mm, back: max. 190 pixels or 29 mm). Otherwise the user may not be able to drag along the whole slider with a single stroke and without releasing the touch.

8.2 Accessible Areas for Direct Touch

When designing the operating systems as well as applications for tablet devices, decisions about the graphical user interface (GUI) layout have to be made, for instance to place menus, items, and widgets. The following aspects are recommended to consider when defining and designing the layout of interactions areas for grasp-based tablet interaction. For further details see Chap. 5.

8.2.1 Midas Touch

Holding a tablet causes already touch events on the back of the device, which are caused by the natural grasp. These have to be understood to distinguish them from intentional touch gestures:

- *Midas Touch*: Touch events on the back of a device are often unintentionally triggered when the device is held.
- *Positions*: The unintended touch events are located very close to the vertical device frame, if the device is held with two hands.
- *Unpredictability*: The vertical position (y-position) of unintended touch events is not predictable.

8.2.2 Accessible Areas

Regarding the definition of interaction areas, three aspects should be considered:

- *Hardly accessible areas*: The horizontal center can barely be reached when the device is held in two hands.
- *Easily accessible areas*: The best accessible areas on tablets that are held with two hands when executing touch gestures are symmetrically located in the horizontal middle regions and vertically close to both device edges for front- and back-of-device touch-based interactions.
- *Midas touch*: The best reachable areas for touch gesture overlap the areas were grasping hands touch the back of the device. Thus, the Midas touch problem has to be considered when classifying touch gestures on the back-of-the device, e.g. through the parameters described in Sect. 8.1.3.
- *Widget placement*: Widgets, such as buttons and sliders, which are located in the center of the interaction area, are not or hard to reach. Thus, widgets should be placed near the vertical edges and in the upper horizontal center, on both, the front and the back of the device. The areas in the center of the device should be avoided for placing buttons and other widgets.

8.3 Pointing Techniques Within and Beyond the Accessible Areas

To control GUI components and widgets, for example when starting an application through tapping on an icon or when changing the speakers' volume through dragging the handle of a volume slider; the control widgets and items have to be selected beforehand. This is usually realized by pointing and selecting the item, which is restricting the accessibility of the tablet's surface during grasp-based interactions. The following guidelines support interaction designers and programmers to define techniques that allow the user to easily select GUI components and widgets.

8.3.1 Direct Touch

In general, direct touch is not appropriate for accessing the center of tablets. However, it is the most common and fastest pointing technique for touchscreens and touchpads. Thus, the limitations of direct touch in grasp-based interaction as well as design recommendations using direct touch in this domain are presented in the following (see Chap. 6 for more details):

- *Ergonomic optimal positions*: Ergonomic optimal positions for accessing widgets via direct touch are located where the digits are hovering while holding the device. On average these optimal points are located at about 59 mm from the vertical frame edge and 84 mm from the upper device edge (including the frame) as shown in Fig. 8.2.
- *Accessibility for direct touch*: Compared to touch gesture interaction, a single touch tap can be used to reach a slightly larger part of the interaction area. This area covers 37 % on the front and 32 % on the back of the interaction area of

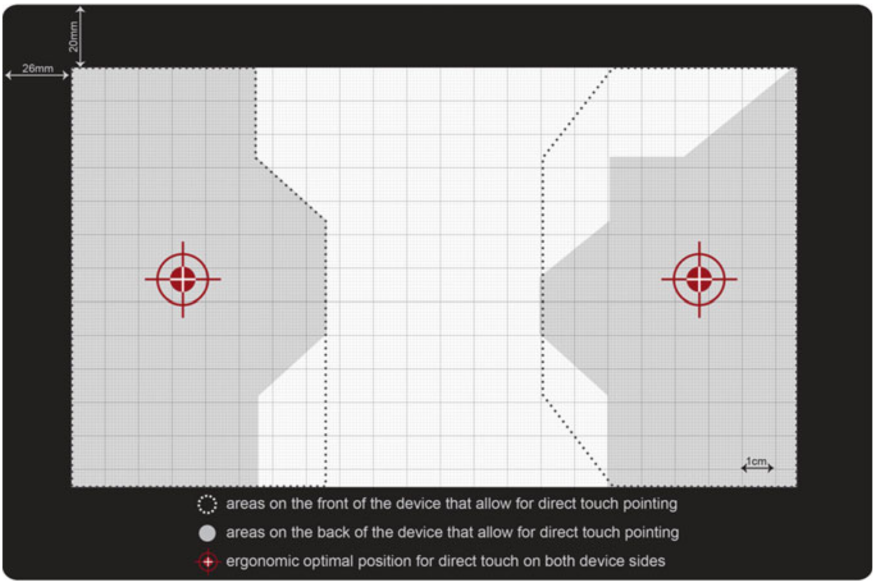

Fig. 8.2 Interaction areas and optimal position for direct touch

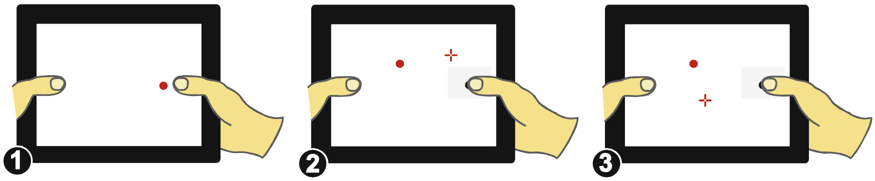

Fig. 8.3 Pointing techniques: (*1*) direct touch (*2*) relative pointing (*3*) miniature area

tablets per hand. Even with both hands, only 74 % on the front and 64 % on the back of tablets is accessible (Fig. 8.2).

- *Adaptive layout*: Users' hands differ in size and the device grasp differ between users and also between situations for the same user. Thus, a dynamic definition of the positions is recommended for placing icons and widgets in the layout. For example, miniature areas and touchpads (as implemented in the experiment that is described in Chap. 7) could appear at the position of a touch.

8.3.2 Indirect Touch

To access the center of the interaction areas on the front as well as on the back of tablets, two indirect pointing techniques (Fig. 8.3) are recommended in the following, while the evaluation that leads to these guidelines is presented in Chap. 7.

- *Relative pointing*: Providing a virtual touchpad, similar to those that are built in laptop, allows moving a cursor through drag gestures over the interaction area. This principle is known. It is more accurate than direct touch but quite slow as several gestures are required for selecting a target. Moreover, a gesture, e.g. a tap, is needed to confirm the selection.
- *Miniature area*: An indirect pointing technique such as the miniature area makes the whole screen easily accessible. This technique is faster than relative pointing, accurate, and thus, a promising alternative technique to select targets that are out of reach using direct touch.

As the miniature area performs equally well on the front as on the back a viable option is to combine direct touch on the front with the miniature area on the back. This approach has the advantage that a dedicated pointing technique is used on each device side which helps to avoid confusion of the user. Furthermore, the whole back of the device becomes easily accessible and thus usable for designers.

Chapter 9
Conclusion and Future Work

This chapter concludes the work presented in this dissertation through recapitulating and contextualizing the contributions. Afterwards recommendations for future work are given.

9.1 Recapitulation and Contextualization of Contributions

While research on human factors in gesture interaction has a long tradition in cognitive ergonomics, the motor ergonomics of gesture interaction has only recently started to be considered. Driven by the aim to increase the usability of tablet devices through providing guidelines for ergonomic design, this dissertation applies different methods, such as expert interviews, user studies and observations using interactive prototypes, questionnaires as well as hand modeling systems.

The particular use case of grasp-based interaction with tablets that are held with a bimanual symmetric grip is defining the design challenges addressed here. The aim was enhancing the usability of tablet devices while enabling more mobility as the current rather static usage scenarios (couch and bed) in which tablets are used (Müller et al. 2012). Thus, the key motivation was enabling interactions with grasping hands while a stable device grip is ensured. The developed guidelines extend the interaction space of tablets that is decreased through the grasp by recommending *ergonomic gestures*, through identifying parts of the *interaction area* that allow for direct touch interaction, and through compensating the limited accessibility in the middle of the interaction area with *indirect pointing* techniques. All of the three topics are considering touchscreen as well as back-of-device interactions.

9.1.1 Ergonomic Gestures

Gestures are the fundamental design units for grasp-based interactions. Thus, an expert-generated ergonomic grasp-based gesture repertoire was identified through

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expert interviews in Chap. 3. The repertoire contains gestures that are feasible while objects or devices are held. For selected gestures (tap, pressure, swipe, and drag), Chap. 4 provides parameters for back-of-device interaction as these differ from touchscreen gestures and corresponding guidelines were missing so far. Furthermore, thresholds for distinguishing back-of-device gestures from touches cause by holding the device to avoid unintentional released commands and frustration of the user are presented. Through the ergonomic gesture repertoire as well as through the guideline for their implementation, fundamentals are provided that support to design tablet interactions that are feasible with grasping hands for both touchscreen and back-of-device interactions. This reduces a research gap as none of such design recommendations existed so far.

9.1.2 Interaction Areas for Direct Touch

In Chap. 5 the areas accessible using direct touch are identified, and it has been shown that these areas overlap on the back with the touch positions when holding the device. These findings indicate ergonomic constraints imposed by the grasp. The center of the touchscreen as well as of the back of tablets cannot easily be accessed via direct touch if the device is held with both hands. Thus, interaction areas for front- and back-of-device interactions were proposed and guidelines that intend to consider these interaction areas as well as to avoid Midas touch problems were provided. The findings about the limitations of direct touch as well as the identification of the relevance of the Midas touch problem for tablet interaction highlight aspects that have to be considered when designing for tablet devices (in contrast to designing for mobile phones). Thus, the knowledge gained about interaction areas helps to identify design challenges that hopefully will be addressed also through future works, similar to the *fat-finger-problem* identified by Siek et al. (2005), which motivated technological inventions, such as *LucidTouch* (Wigdor et al. 2007), a device that allows the user to interact on the back.

9.1.3 Pointing Techniques Beyond Direct Touch

The lack in accessibility of the central interaction areas of tablet devices causes problems with one of the most important interaction techniques for touchscreens, which is pointing through direct touch. To provide biomechanical insights in direct touch pointing, Chap. 6 investigated ergonomics of touch-based pointing on both tablet sides. An optimal area that is best accessible via direct touch was identified. This area is located where the digits have a relaxed pose, which neither is stretched nor required to bend the joints much. As accessing the center of the interaction areas is highly important for tablet interaction and as direct touch fails here, in Chap. 7 three pointing techniques, which allow for accessing targets further away, were compared with the common direct touch technique. While direct touch was the fastest, relative pointing using a touchpad, an inverse cursor, and direct touch on a miniature interaction area enable to reach targets that are not accessible through direct touch. The miniature interaction area was shown to be the best for targets that are not reachable with direct touch; and design guidelines for pointing techniques for grasp-based tablet interactions were recommended.

The majority of this dissertation's contributions has been published in selective peer-reviewed academic conferences or have been submitted to them as well as to a journal:

Wolf, K. 2011. Microinteractions beside ongoing manual tasks. In *Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction* (TEI '11). ACM, New York, NY, USA, 447-448.

Wolf, K., Naumann, A., Rohs, M., and Müller, J. 2011b. Taxonomy of micro-interactions: defining microgestures based on ergonomic and scenario-dependent requirements. In *Proceedings of the 13th IFIP TC 13 international conference on Human-computer interaction - Volume Part I* (INTERACT'11), Pedro Campos, Nuno Nunes, Nicholas Graham, Joaquim Jorge, and Philippe Palanque (Eds.), Vol. Part I. Springer-Verlag, Berlin, Heidelberg, 559-575.

Wolf, K. 2012. When hand and device melt into a unit: microgestures on grasped objects. In *CHI '12 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '12). ACM, New York, NY, USA, 959-962.

Wolf, K. and Henze, N. 2014. Comparing Pointing Techniques for Grasping Hands on Tablets. Accepted *to* the *16th international conference on Human-computer interaction with mobile devices and services companion* (MobileHCI '14). ACM, New York, NY, USA, 10 pages.

Wolf, K., Schleicher, R., and Rohs, M. 2014a. Ergonomic Characteristics of Touch Gestures for Front- and Back-of-Tablets Interaction with Grasping Hands. Submitted to the *16th international conference on Human-computer interaction with mobile devices and services companion* (MobileHCI '14). ACM, New York, NY, USA, 6 pages.

Wolf, K., Schleicher, R., Kratz, S. and Rohs, M. 2014b. Touch Accessibility on the Front and the Back of Tablets. In *Proceedings of EuroHaptics 2014*, 8 pages.

Wolf, K., Schneider, M., Mercouris, J., and Hrabia, C.-E. 2014c. Front- and Back-of-Tablet Pointing with Grasping Hands. *International Journal of Mobile Human Computer Interaction* (IJMHCI).

The listed publications are co-authored by other researchers that advised the author or collaborated with her as well as by students that were supervised by the author. Anja Naumann, Michael Rohs, and Jörg Müller advised the paper writing in Wolf et al. (2011). Niels Henze helped with the implementation as well as with paper writing in Wolf and Henze (2014). Robert Schleicher and Michael Rohs advised the study design and gave valuable comments in writing the papers Wolf et al. (2014a, b). Markus Schneider, Christopher-Eyk Hrabia, and John Mercouris built the two apparatuses in Wolf et al. (2014c) under the supervision of the author during their theses and internship.

9.2 Future Work

In this thesis, a series of contributions in the domain of grasp-based touch interactions are presented. A number of open research questions and unsolved challenges were identified while conducting the research presented in this thesis. This thesis focusses on touch gestures performed with the hands that grasp a tablet with a symmetric bimanual grip. In the following sections the most promising directions for future work are highlighted. In particular, considering different grasp types, evaluating form factor beyond tablets, investigating different gestures, and investigating if established pointing models fit grasp-based pointing is discussed.

9.2.1 Evaluating Different Grasp Types

This thesis focusses on the most important way to hold a tablet for enabling mobile usage; using a symmetric bimanual grip to hold tablets in landscape format. There are, however, other ways to hold a tablet that require further investigation.

In the user experience guidelines of Microsoft (2012), beside the bi-manual grip, three other ways are mentioned, such as (1) one hand holding, while the other hand is "free" for interacting (2) resting the tablet on the legs (3) the device rests on a table. For instance, Wagner et al. (2012) investigated grip 1 and proposed Bi-touch, an interaction technique that enables to interact with the support hand that holds the device. User studies that aim to contribute towards understanding ergonomics on interacting with tablets using the support as well as the "free" hand are still missing; and works similar to those carried out in this dissertation but focusing on a one-handed grip would provide an understanding of tablet interactions beyond the bimanual grasp-based scope of this thesis.

The accessible part of the interaction area of the grasping hand is suggested to be smaller than the one of the hands holding the device with a bimanual grip as holding a tablet with one hand makes the grip less stable. As shown by Wagner et al. (2012), interactions with the support hand are valuable. Thus, investigations of the accessibility of the interaction area as well as exploring which gestures are feasible using the supporting hand would contribute to this use case.

9.2.2 Evaluating Interacting with Form Factors Beyond Tablets

This thesis focusses on grasp-based interacting with tablet devices. An extension of this thesis would be work that investigates to which extend the contributions of this dissertation can be transferred to grasp-based interactions with devices that have different form factors. The form factor can, for example, differ from tablets in size and shape.

The screen size of the used device was 10.1 inch; and future work should investigate if the found accessibility of interaction areas can be used for further screen sizes. Moreover, the fraction of the screen that is easily accessible will become even smaller for larger screens. It would also be interesting to investigate if the finding on pointing techniques for far away targets can be transferred to much larger tabletops where interaction is not restricted by hand size but by arm length.

In the future, the shape of devices may be designed with more respect to grasp ergonomics; and tablet devices may have curved surfaces. Roudaut et al. (2011) investigated touch on curved surfaces; and in Wolf et al. (2013) the possibility to perform gestures on convex as well as on concave surfaces was evaluated. Research that investigates the touch accessibility on curved tablet surfaces would test if the accessibility is similar to flat surfaces. Furthermore, drag and swipe gestures performed on curves may be different. Research similar to the one presented in Chap. 4 would show if the parameters for gesture detection change with the surface they are executed on.

9.2.3 Considering Different Gestures

The gestures that were considered in the experiments of this thesis were selected from the expert-defined gesture repertoire presented in Chap. 3. The selection of the gestures that were considered during the follow-up experiments was driven by the touchscreen technology. Touch gestures are commonly detectible using 2D touch information, which is triggered by skin contact with the surface and contains contact position data.

Modern touchscreens and depth cameras, which may soon be built in mobile devices, allow using more than 2D touch information. Touch is a 3D event, which also contains information about the incoming angle of a finger. This extends the gesture design space by one spatial dimension. The topic has started to be investigated with a focus on interface development and 3D touch gesture detection (Dippon and Klinker 2011; Ketabdar et al. 2010; Kratz et al. 2013; Rogers et al. 2011), but not with a focus on biomechanics.

Trudeau et al. (2012) found that the 3D pose of a digit influences touch-based pointing performance with mobile phones; and this thesis showed in Chap. 6 that the influence of biomechanics on pointing performance can be transferred to tablet interactions. Thus, it is assumed that the performance of other 3D touch gestures than direct touch is also affected by the biomechanics of the hand.

Research on biomechanics in 3D touch gesture execution beyond direct touch is a research gap and addressing it would extend the presented dissertation.

9.2.4 Modeling Pointing Performance for Grasping Hands

Since Fitts proposed his law (Fitts 1954) to model human movement and to predict the time required to rapidly move to a target area (considering the distance to the target and the size of the target), there have been many studies on selection time models conducted on touch screens. Most of them, however, use an apparatus that is controlled by a hand that is not holding the device. Common examples are mobile phones that are held with one hand while the other is used for pointing; Bi et al. (2013) used such an apparatus to develop FFitts law. Other examples are large touch screens that are not held such as DiamondTouch that Bützler et al. (2012) used. Studies using devices which are held and operated with the same hand generally have not focused on selection time models; Wobbrock et al. (2008) used the Shannon formulation of Fitts' Law (MacKenzie and Buxton 1992) as a tool to compare different ways of holding and using the device. While one-handed pointing was modeled for phones (Karlson and Bederson 2007; Parhi et al. 2006; Perry and Hourcade 2008), research concerning the validity of current models when operating and holding tablet devices is rare. Oulasvirta et al. (2013) modeled text entry performance on tablets. They split the keyboard and thereby considered the outer regions but not the center of the device. Pointing and target selection time over the entire tablet surface while the device is held with two hands has to the author's best knowledge not been modeled.

In Chap. 6, research on pointing on tablets was conducted. It has been shown for direct-touch pointing that target acquisition time decreases over distance until an ergonomic optimal point is reached, where the thumb or the fingers have a relaxed posture. While the found target acquisition time is contradictive to Fitts' Law for positions further away than the ergonomic optimal point, target acquisition time increases as predicted by a Fitts' Law model. A similar trend occurs for other grasp-based pointing techniques, e.g. relative pointing, as shown in Chap. 7.

Thus, investigating if Fitts' Law allows for predicting target acquisition time for grasp-based pointing would extend the findings of this dissertation and contribute to the topic of pointing on tablets with grasping hands.

9.3 Closing Remarks

Tablet are mobile devices; but they are currently mainly used when sitting on the couch or lying in bed. So far, interacting with tablets follows the design guidelines for mobile phones; and most interactions require to hold the device with one hand and to use the other to interact with the device. Thus, the current interaction design of tablet devices does not support grasp-based interactions with a symmetric bimanual grip. This grip, compared with resting the device on the lap or holding it with one hand, is more stable and more appropriate for mobile scenarios when the device is carried around.

The contributions of this dissertation support interacting with tablets while holding them stably. This will allow for extending the use of tablets and to enrich the usability of applications beyond personal communication and entertainment, such as being a portable device for controlling smart environments and buildings or enabling doctors to access patient data during medical rounds. The contributions of this thesis can guide interaction designers and programmers to develop tablets applications for a wide range of domains that are ergonomic, usable, and fun to use.

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