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Suitability of Touch Gestures and Virtual Physics in Touchscreen User Interfaces for Critical Tasks

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Zusammenfassung

Das Ziel dieser Forschungsarbeit war es zu untersuchen, ob moderne Touchscreen-Interaktionskonzepte, die auf Consumer-Electronic-Geräten wie Smartphones etabliert sind, für zeit- und sicherheitskritische Anwendungsfälle wie Maschinensteuerung und Medizingeräte geeignet sind. Mehrere gebräuchliche Interaktionskonzepte mit und ohne Touch-Gesten und virtueller Physik wurden experimentell auf ihre Effizienz, Fehlerrate und Nutzerzufriedenheit bei der Aufgabenlösung untersucht. Basierend auf den Resultaten werden Empfehlungen für das Scrollen in Listen und das horizontalen Navigieren in mehrseitigen Software-Dialogen ausgesprochen.

Der Text gibt eine Übersicht der speziellen Eigenschaften von Touchscreen-Mensch-Maschine-Schnittstellen und der Unterschiede zu zeigerbasierten Eingabegeräten. Er beschreibt den aktuellen Stand des Touchscreen-Interaktionsdesigns, v.a. die Besonderheiten moderner Touch-Interaktion, nämlich Touch-Gesten und virtuelle Physik. Die größten Herausforderungen für Touchscreen-Interaktionsdesign sind Feedforward, Feedback, Größe der interaktiven Elemente, Kompatibilität, Effekte virtueller Physik und Interferenz. Basierend auf einem einfachen qualitativen Modell der Einflussfaktoren beim Touchscreen-Interaktionsdesign sollten die folgenden Hypothesen zu Effizienz und Sicherheit moderner Touchscreen-Interaktion überprüft werden: Touch-Gesten führen zu langsamerer Aufgabenerfüllung, höherer Fehlerrate, aber besserer Nutzerbewertung. Beim Scrollen führt virtuelle Trägheit zu schnellerer Aufgabenerfüllung, aber auch zu mehr Über-das-Ziel-Hinausschießen und höherer Fehlerrate. Seitenweises Blättern führt zu schnellerer Aufgabenerfüllung und geringerer Fehlerrate als kontinuierliche Inhalte. Um dies zu überprüfen, wurden mehrere Experimente durchgeführt, die Interaktionskonzepte häufiger Aufgaben vergleichen: Menüs, Funktionswähler, Zahleneingabe, Listen-Scrollen und horizontaler Ansichtswechsel. Der Einfluss des Interaktionsdesigns auf Eingabegeschwindigkeit, Fehlerrate und Nutzerbewertung wird für Listen-Scrollen und horizontalen Ansichtswechsel deutlich gezeigt. Eine mit Wischgesten gesteuerte Liste mit virtueller Trägheit und Alphabetleiste ist die beste Wahl für das Scrollen von Listen aller Längen. Um horizontal durch Ansichten zu navigieren, sind Tabs die geeignetste Wahl für kritische Aufgaben. Touch-Gesten können zu höherer Fehlerrate führen, aber vernünftig gestaltete Konzepte mit Touch-Gesten können dennoch für kritische Aufgaben geeignet sein. Die Nutzerbewertung von Touch-Interaktionskonzepten korreliert stark mit der Eingabegeschwindigkeit. Fehler scheinen keinen Einfluss darauf zu haben.

Abstract

The goal of this research was to examine if modern touchscreen interaction concepts that are established on consumer electronic devices like smartphones can be used in time-critical and safety-critical use cases like for machine control or healthcare appliances. Several prevalent interaction concepts with and without touch gestures and virtual physics were tested experimentally in common use cases to assess their efficiency, error rate and user satisfaction during task completion. Based on the results, design recommendations for list scrolling and horizontal dialog navigation are given.

The text gives an overview of the special characteristics of touchscreen human–machine interfaces and their differences to pointer-based input devices. It describes the state of the art of user interface design for touchscreens, particularly the interaction concepts that distinguish modern touchscreen interaction with tablets and smartphones from older interaction concepts, namely touch gestures and virtual physics. Due to the use of these interaction concepts and the special characteristics of touchscreens, the main challenges of user interface design for touchscreen are feedforward, feedback, size of interactive elements, compatibility, effects of virtual physics, and interference. Based on a simple qualitative model of influence factors in touchscreen interaction design, the following hypotheses concerning the efficiency and safety of modern touchscreen interaction are to be tested: Touch gestures lead to slower task completion, higher error rate, but better user rating. For scrolling tasks, virtual inertia leads to faster task completion, but more overshooting and higher error rate. Paged content leads to faster task completion and lower error rate than continuous content. To test the hypotheses, several experiments were conducted that compare interaction concepts in common tasks: Menus, function selectors, numerical input, list scrolling, and horizontal content change. For list scrolling and horizontal content change, the influence of interaction design on input speed, error rate, and user rating is clearly shown. A list that can be moved with a swiping gesture and that has virtual inertia and an alphabetic index bar is the best choice for scrolling lists of all lengths. To navigate through horizontal content, tabs are the most suitable choice for critical tasks. The use of touch gestures can lead to higher error rates, but reasonably designed concepts with touch gestures can still be suitable for critical tasks. The user ratings of touch interaction concepts correlate strongly with the input speed. Errors and overshoots seem to have no impact.

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Everything is best for something and worst for something else.

— Bill Buxton

1 Introduction

Displays that can not only output information, but also detect and localize touches on their surface to serve as an input device, have been available for several decades now and are a proven and common input technology in many modern electronic devices. These touchscreens offer a number of advantages over other input devices like keyboards, mice, touch pads, voice or gesture recognition. They need almost no additional space in all devices that already have displays. By closely integrating input and output, they allow for a form of human–computer interaction that can be considered especially direct because information presentation, user input and visual feedback all take place at the same location.

Although touchscreens are a long-standing technology (Shneiderman, 1991) as far as computer technology is concerned, they have only become as important and ubiquitous as they are today in the last few years. Because of vast technical improvements and an ongoing process of miniaturization, touchscreens are today available and suitable for a wide variety of device classes, foremost for numerous forms of mobile devices. Especially the establishment of smartphones, which began with the iPhone in 2007, has put a mobile touchscreen device in almost everybody's pocket. Tablets and convertible laptop computers continue to add to the success of the touchscreen. With these new device classes, new interaction paradigms were introduced and established, mainly by the most successful vendors Apple, Google, and Microsoft. These new paradigms make use of the improved abilities of modern capacitive touchscreens to detect sliding finger motions on the screen continuously and without delay (Figure 1). Faster microprocessors allow instantaneous and realistic dynamic visual feedback based on physical metaphors. Touch gestures and virtual physics have become state of the art in touchscreen devices and they are used in almost all modern consumer electronics.

Yet the high rate of innovation of user interfaces that is driven by the high-volume market and short development cycles of consumer electronics, which allow for fast return of investment and quick changes in strategy, has not arrived in other fields. Where investment cycles are longer lasting, introduction of new technologies will occur with a delay. More importantly, in fields where the human–computer interaction is part of a task that might have severe consequences for economic profitability or human safety, decision makers are more likely to trust in proven concepts than to adapt young technologies (Hartmann, 2012; Wiedenberg, 2012). Therefore, although gesture-based touchscreen interaction has been the state of the art for some time, it is only adapted slowly in factories, power plants, process engineering and medical devices.

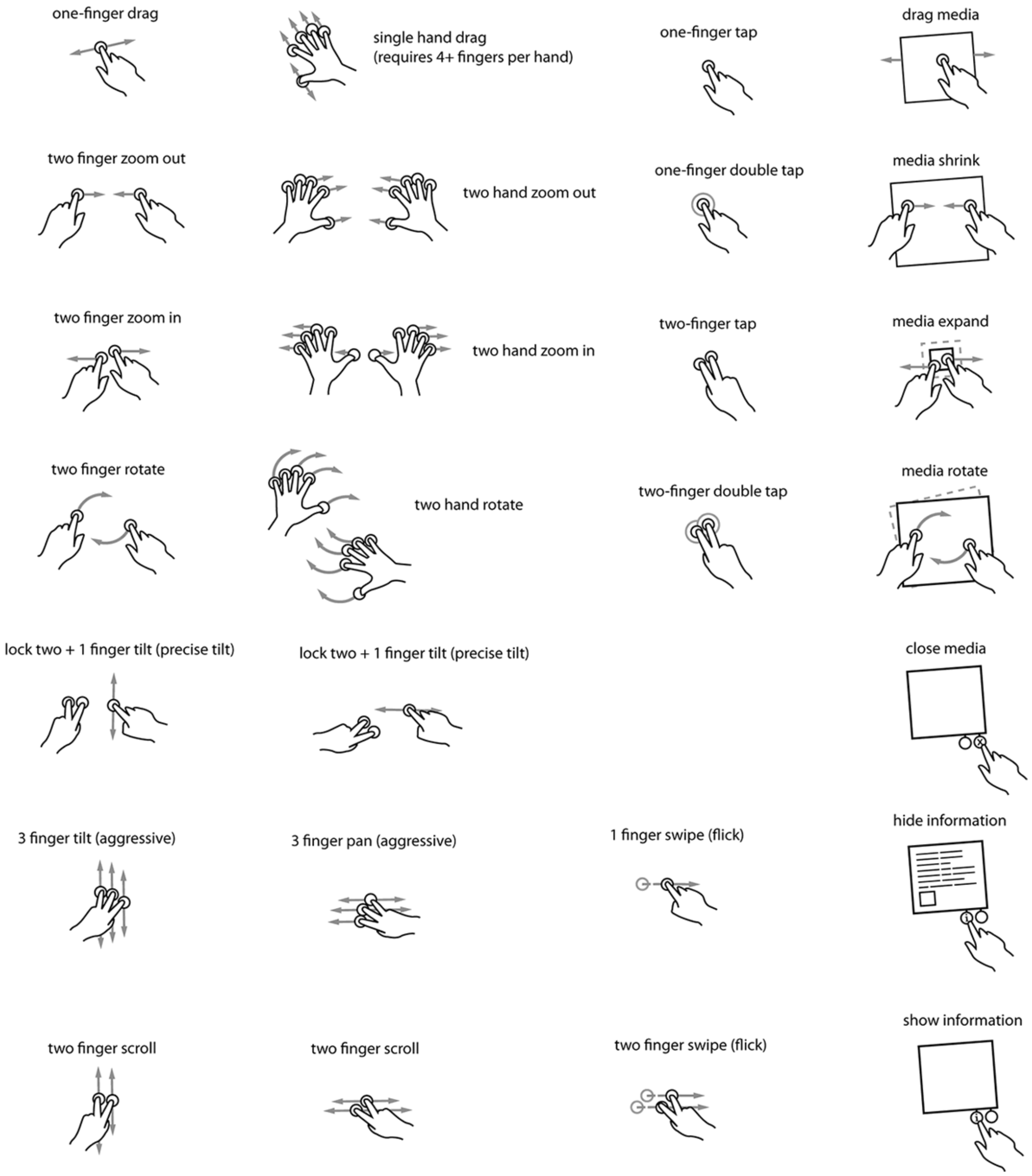

Figure 1: An overview of possible touchscreen gestures. [Source: gestureworks.com]

While they have been using touchscreen technology for many years, they tend to offer conservative virtual-button-based user interfaces (Figure 2). Others copy elements of consumer electronic user interfaces without any adaption to the circumstances of their field of application. Moreover, some develop new interaction concepts without any experimental validation, which is concerning from an ergonomic point of view.

Figure 2: An engineer using a touchscreen in an industrial environment. [Source: www.heidenhain.de]

For an adaption of modern interaction paradigms and a suitable and correct implementation in the devices, easily applicable and scientifically verified guidelines are needed that explicitly address touchscreen interaction for critical tasks without arbitrary focus on vendor-specific hardware, software frameworks or visual design strategies. This thesis documents research that aims to find and validate touchscreen interaction paradigms that are suitable for critical tasks. Certain use cases were studied to give recommendations of ergonomic design while tapping the full potential of modern touchscreen technology.

2 A Short History of Touchscreen Interaction

Interacting with objects directly on a computer screen is a technology almost as old as electronic computers themselves. At first, it was only possible with stylus-like devices, called light guns or light pens (Figure 3), which were used as early as 1952 with the MIT's Whirlwind computer (Carlson, 2009; Freedman, 2015).

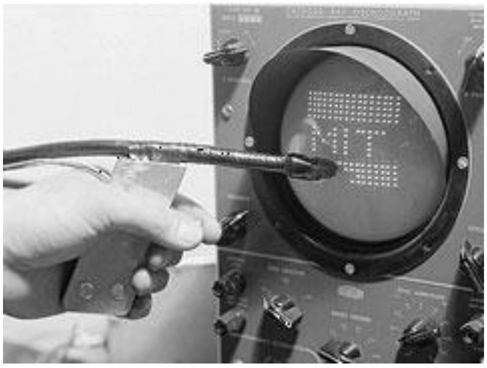

Figure 3: MIT's Whirlwind computer was the first to allow for direct interaction on the screen using a light pen. [Source: https://history-computer.com/ModernComputer/Electronic/Whirlwind.html]

The first descriptions of the mode of operation of capacitive touchscreen and working prototypes of 'touch displays' that could be operated with the fingers were published by Johnson in the 1960s (Johnson, 1965, 1967). They were intended for radar operators as described by Orr and Hopkins (1968), who were the first to analyze the potential of this new input technology to improve the workplace and performance of air traffic controllers. These early touchscreens used thin copper wires stretched over the display, which obstructed the view of the operator somewhat depending on the density of the wire matrix (Figure 4).

The first transparent touchscreen was developed and put to daily use at CERN in the early 1970s, but it was originally only able to detect nine different touch areas on the screen, later sixteen (CERN, 2010). Touchscreens spread more with the invention of optical touchscreens in 1972 (US3775560, 1973) and were integrated into computers like the University of Illinois' PLATO IV system (Figure 6) and in 1983 into the commercially available HP-150 (Figure 7; YouTube, 2008). The first computer input system that allowed multi-touch was a camera-based touch pad rather than a touchscreen (Mehta, 1982).

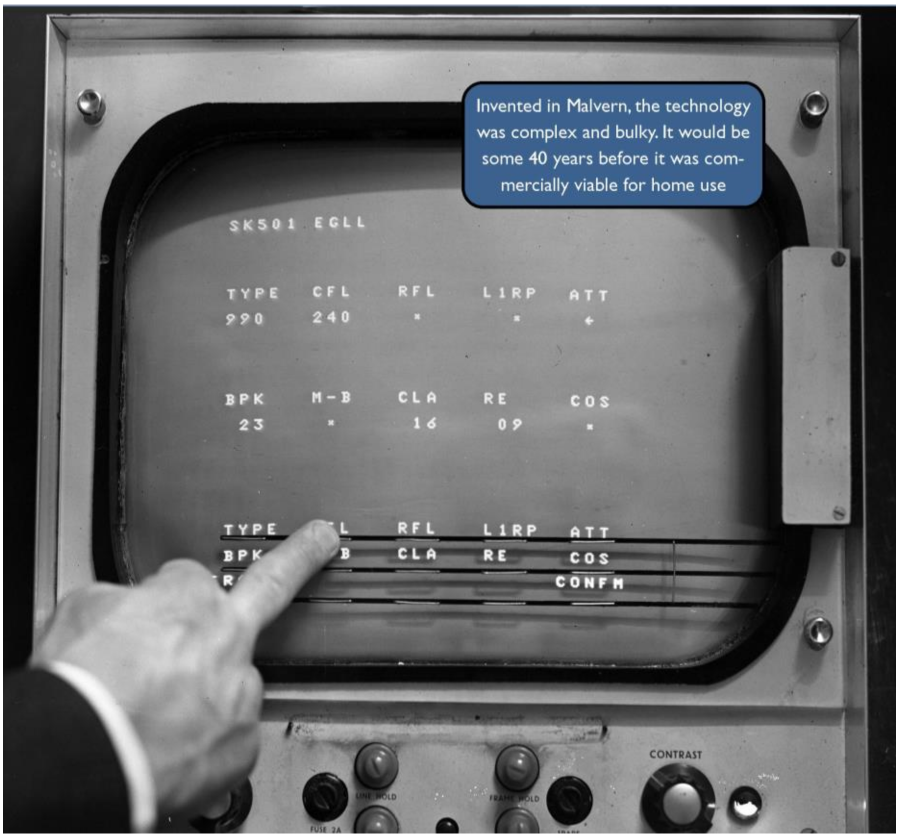

Figure 4: The first touchscreen had visible wires running across the screen. [Source: mraths.org.uk]

Figure 5: The first transparent, capacitive touchscreens (bottom) were developed and used at CERN. [Source: https://cerncourier.com/the-first-capacitative-touch-screens-at-cern/]

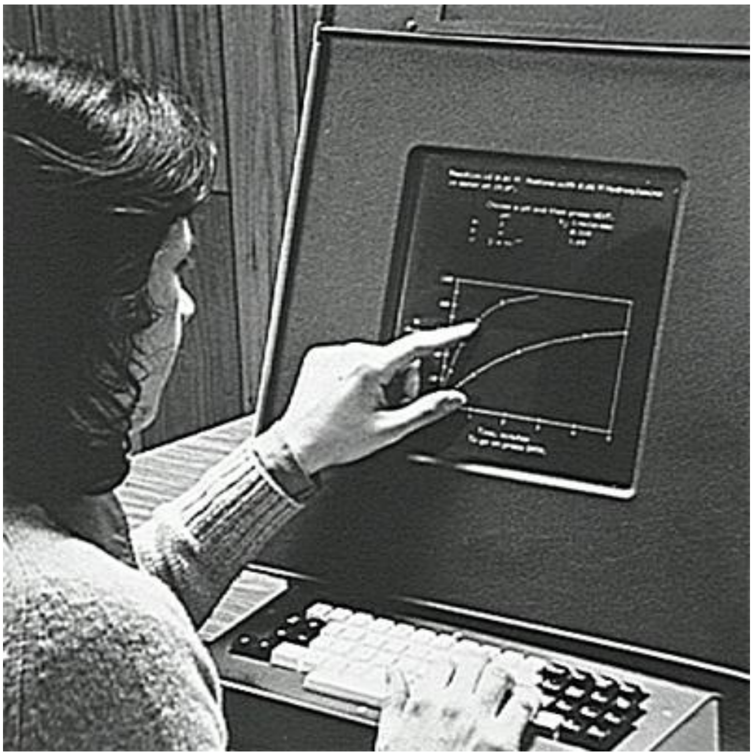

Figure 6: The University of Illinois' PLATO IV computer system was the first widely deployed computer with optical touchscreen. [Source: https://archives.library.illinois.edu/erec/University%20Archives/1505050/BrownBag/BBPlatoIV.htm]

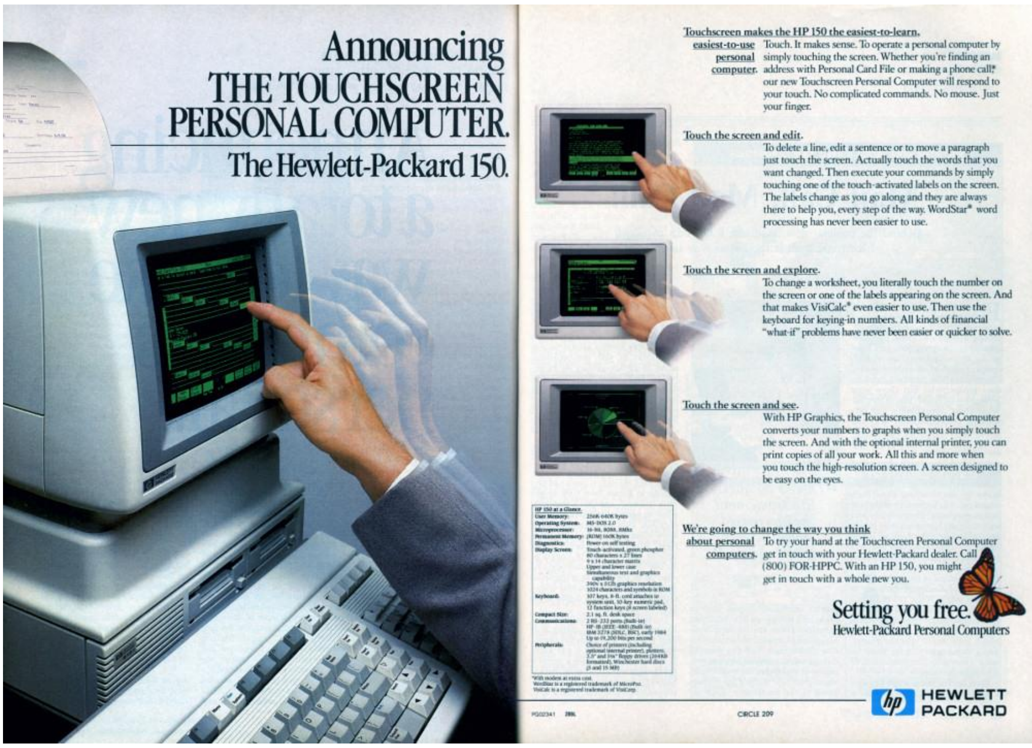

Figure 7: The Hewlett-Packard 150 computer system was the first commercially available touchscreen computer. [Source: http://www.vintagecomputing.com/index.php/archives/356/retro-scan-of-the-week-the-hp-150-touchscreen-computer]

Krueger (1983, 1991) was the first to describe in depth the possibilities of gestural human–computer interaction without additional technical devices (e.g. mouse, stylus, glove) on the basis of Video Place and later Video Desk (Krueger, Gionfriddo, & Hinrichsen, 1985). Although those systems were not touchscreens in the narrow sense, in one of the described configurations they worked like modern touch tables. Transparent capacitive touchscreens with multi-touch capabilities were developed at Bell Labs in 1984 (US4484179, 1984). Although it had to be controlled with a stylus, the GRiDPad (Figure 8) was the first self-contained mobile touchscreen device in 1989 (Atkinson, 2008).

Figure 8: The first self-contained mobile touchscreen device, the GRiDPad. [Source: https://oldcomputers.net/gridpad.html]

In 1993, Wellner (1993) showed with the DigitalDesk how touchscreen interaction can be used to augment a work environment like a classic desktop. The first commercially available portable device with a finger-operated touchscreen was the IBM Simon (Figure 9), considered the first smartphone by some (Buxton, 2007). It was sold between 1994 and 1995. To address the limitations of touchscreens concerning haptic feedback, tangible interfaces were introduced in 1995 (Fitzmaurice, Ishii, & Buxton, 1995). The Portfolio Wall by Alias|Wavefront was a commercially available wall display that recognized many of the now common touch gestures for direct manipulation and menu control in 1999 (Buxton, 2007). By 2001, the Diamond Touch table by Mitsubishi Research Labs (Figure 10) was able to distinguish applied pressure and hands and fingers of different users (Dietz & Leigh, 2001). In 2002, Rekimoto (2002) introduced a sensor technology that is able to recognize hand positions, shapes and their distance from the surface. This capacitive system does not suffer from light occlusion problems like camera-based ones and can be fully integrated into the surface.

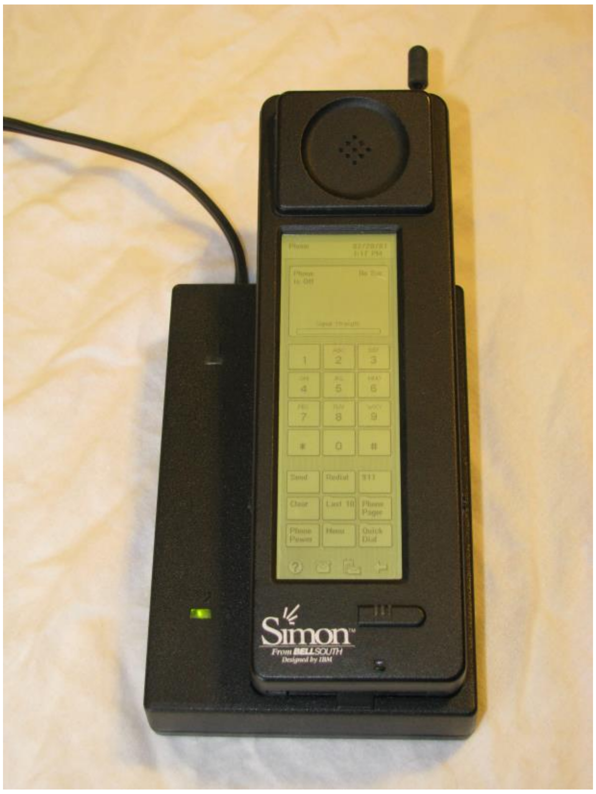

Figure 9: The IBM Simon from 1994 is considered the first smartphone by some. [Source: https://commons.wikimedia.org/wiki/File:IBM_SImon_in_charging_station.png]

Figure 10: Diamond Touch is a touchscreen table that can be interacted with by several users. [Source: MERL-LOBBY by Mergatroid212; https://en.wikipedia.org/wiki/File:MERL-LOBBY.JPG ; license: CC BY 3.0]

The Neonode N1 (Figure 11), available in 2004, was the first smartphone to use a touchscreen as primary input and to support touch gestures for several functions (Blickenstorfer, 2006; Joire, 2007). Its vibration motor offered some sort of haptic feedback. The Lemur music controller (Figure 12) was the first commercially available touchscreen device with unlimited touch points in 2005 (Stantum Technologies, 2015).

Figure 11: The first smartphone to support touch gestures: The Neonode N1 [Source: http://www.gsmhistory.com/vintage-mobiles/fig-36-neonode-n1/]

Figure 12: The Lemur music controller was the first commercially available touchscreen device that supported unlimited multi-touch. [Source: http://www.jazzmutant.com/]

PlayAnywhere was the first touch table that was able to identify and interact with objects. It displayed corresponding visual output to enhance the possibilities of tangible interfaces (Wilson, 2005). It led to a commercial product in 2007, the Microsoft Surface, later renamed PixelSense (Robertson, 2012). In its latest iteration, Samsung SUR40 (Figure 13), it is also an image processor, like a camera (Microsoft, 2015a) and can detect objects even at some distance.

Figure 13: Touchscreen tables like the Samsung SUR40 allow multi-touch gesture interaction and can recognize objects that lie on the surface. [Source: http://nsquaredblog.blogspot.com/2012/07/australian-launch-event-for-samsung.html]

However, the main cause for today's massive ubiquity and popularity of touchscreen devices are modern smartphones and tablets, which were made popular by Apple beginning in 2007 (Figure 14) with the iPhone and in 2010 with the iPad (Figure 15). The ongoing commercial success of these device classes leads to rapidly rising sales of touchscreens (Figure 16) and to a continuing integration of touchscreens into a wide variety of electronic devices like home appliances, industrial machines, and medical equipment.

Figure 14: The devices that defined modern touchscreen interaction: The original Apple iPhone (2007) [Source: https://www.macworld.com/article/3204152/original-2007-iphone-photo-album.html]

Figure 15: In 2010, Apple increased the ubiquity of touchscreen devices by introducing the iPad. With tablet computers, mobile touchscreen interaction is not limited to small screens anymore. [Source: https://www.macwelt.de/a/ipad-1-das-kann-das-erste-apple-tablet-heute-noch,3060023]

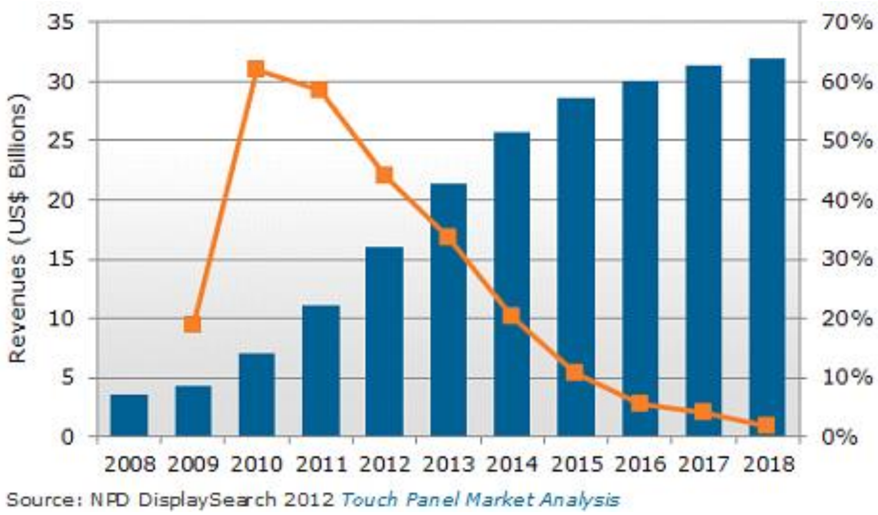

Figure 16: Annual touchscreen revenues and forecast based on 2012 data. [Source: https://www.prweb.com/releases/npd-displaysearch/analysis/prweb9705889.htm]

3 Human Factors in Touchscreen Interaction

3.1 Fundamentals of Human–Computer Interaction

3.1.1 Criticality of Tasks

This thesis focuses on the evaluation of modern software user interfaces on touchscreen devices intended for use cases where operators have to fulfill critical tasks. The notion of critical tasks is known in a variety of fields, notably in project management, where it describes a task in a project that lies on the critical path and thus influences the time plan of the project. It was originally called critical jobs by the inventors of Critical Path Planning, Kelley and Walker (1959). Another common use of the concept of critical tasks deals with their effect on human safety. The definition used in this thesis is mainly based on the latter, safety-critical tasks, which is the predominant meaning in the field of human factors. Yet it is extended to include economic requirements, which are essential to most industrial use cases that are part of the motivation for this research. This secondary focus on efficiency shows ties to the role of criticality in Critical Path Planning. All mentions of critical tasks in this text refer to tasks that can have significant influence on the safety of humans or the economic viability of a process, as defined by the Department of Defense (2013): "A critical task is one requiring human performance which, if not accomplished in accordance with system requirements, will likely have adverse effects on cost, system reliability, efficiency, effectiveness, or safety." The criticality of the common intended tasks distinguishes touchscreen interaction with most consumer electronics from interaction with devices for healthcare, facility management, and plant control. Those environments, where tasks as defined by the Department of Defense can occur or are part of the regular line of action, will be called "critical task environments" in this text. The following factors mainly influence the criticality of tasks.

3.1.1.1 Risk

The main difference between a critical task and a non-critical task is that there is a significant risk of unsuccessful completion of the task. Farmer (1977) defined risk as the product of the probability of an event and the adversity of its results. This means the task is either hard to complete successfully or the consequences of an unsuccessful completion are severe (or both). As mentioned above, this can concern either the safety of the people and the material involved or the economic viability of the process that contains the task. Tasks with high risk usually result in high costs to achieve acceptable system reliability, effectiveness, efficiency, and safety. An unsuccessful completion of the task is the result of some kind of error during the procedure. The error can occur on the part of the machine or on the part of the user. The focus of this research lies in the human–machine interface, so it is mainly concerned with understanding and minimizing the risk that is a result of the design of this interface or can be influenced by the design of the whole man–machine system. Machine failures may be unavoidable and not be caused by user actions, but may require the possibility of restarting gracefully and lessen consequences. This adds additional requirements to the human–machine interface, where this restarting or additional adjustment processes have to be triggered. Human errors may be results of individual capabilities or circumstances, but are often also strongly influenced by the design of the human–machine interface (Reason, 1990).

3.1.1.2 Time Budget

If one follows the criticality definition by the Department of Defense (2013), critical tasks can be found in any corporate environment because here most tasks have to be effective and efficient to assure the economic viability of a company. If tasks can be completed faster, more can be accomplished in the same time frame. This increase in efficiency is desirable from an economic point of view. Therefore, while there is no immediate necessity for the users to operate faster than they would normally, the organizational process might include incentives to do so (e.g. wages or career advancement dependent on throughput).

The time budget can also be clearly defined by process design. In any non-trivial process, tasks are usually dependent on certain circumstances, usually induced by other tasks. To assure the effectiveness and efficiency of those tasks, they often have to be completed within a loosely or very concisely defined time frame. If there is a clear dependency on another task, the time frame begins with the completion of this preceding task. If the result of the preceding task is not permanent, the following task cannot be carried out successfully anymore at some point. While this dependency on other tasks is often a result of economic considerations in industrial applications, it can also be a result of technical restrictions, medical requirements, or other uncontrollable circumstances. Examples would be working on a product while it is hot enough to be formed or examining a patient while a medication is in effect.

Repeatedly working on tasks under high time pressure is known to worsen performance and increase human error (Reason, 1990; Schmidtke, 1993), thus influencing economic viability and possibly safety. If a time budget is inherent in a task, the design of the man–machine interface has to ensure the best possible usage of this time frame. This means that the number of necessary steps, required precision, and the cognitive and physical workload should be as low as possible. Since the performance of users with technical systems is influenced by their familiarity with these systems and their understanding of them, the system design must facilitate learning and understanding.

The possible generalization of design recommendations for critical tasks decreases with the conciseness of the time budget. This conciseness is usually a result of a strong dependence on other specific tasks or activities in the process. That is why recommendations for better efficiency cannot be generalized easily. Moreover, measures to improve efficiency of tasks with concise time budgets are usually highly specific to properties and circumstances of the task. This research focuses on tasks with a general requirement for high efficiency, but without concise time budgets because this would make generalization of recommendations less valid and require different approaches in experiment design.

3.1.2 Usability

Usability is one of the important factors users consider when choosing a product (Mack & Sharples, 2009). Ensuring the usability of a technical system is the main goal of ergonomics, human factors engineering, and related disciplines. The main motivation behind this research is to broaden the knowledge about factors that influence the usability of touchscreen interaction concepts.

3.1.2.1 Definition

The commonly taught and accepted definition of usability is documented in the ISO standard 9241 “Ergonomics of Human System Interaction” as “the effectiveness, efficiency and satisfaction with which specified users achieve specified goals in particular environments”; where effectiveness means “the accuracy and completeness with which specified users can achieve specified goals in particular environments”; efficiency means “the resources expended in relation to the accuracy and completeness of goals achieved”; and satisfaction means “the comfort and acceptability of the work system to its users and other people affected by its use”. (DIN EN ISO 9241-11:1998)

3.1.2.2 Effectiveness and Efficiency

While effectiveness in the general sense of achieving the specified goal is the paramount objective of all system design, rating the outcome of the use of a machine can be problematic. While some tasks may have a simple binary outcome (successful/unsuccessful), others can lead to a variety of outcomes with differing value for the users (and possibly their employer). Assessing the accuracy or quality of the reached solution on a spectrum is often difficult, subjective and highly dependent on the specific task. Since one goal of this research is to give recommendations that can be applied to a variety of use cases instead of very specific tasks, effectiveness seems an unsuitable measure for assessing interaction concepts in this context. Therefore, the focus of this research is the efficiency in task completion under the assumption that the intended goal can always be reached. Assessing efficiency can also be difficult because the effort spent to reach the goal consists of both objective measures like time to completion and subjective measures like cognitive workload. Nevertheless, these attributes are relevant for all tasks. Therefore, it is possible to make general recommendations for human–machine interface design if factors are found that influence the efficiency of certain interaction concepts.

3.1.2.3 Satisfaction

Satisfaction is an important usability metric that can easily be analyzed using e.g. questionnaires and interview techniques. However, it only determines the absence of factors that negatively influence the users’ perception of a human–machine interface without necessarily measuring the variety of factors that might enhance their experience beyond the necessary and the expected. While two variants of interaction concepts might be equal in effectiveness, efficiency, and satisfaction for the users, one might lead to a better overall experience because of factors not considered in classical usability assessments. This is why the broader concept of user experience (see 3.1.2.5) has become relevant in the field of human factors today. In this research, the metrics for user satisfaction will be merged with modern user experience metrics.

3.1.2.4 Error Rate

Error rate means the amount of errors a user makes when trying to achieve the intended goal with a given interaction concept. An error is an activity or lack of activity by the user that increases the necessary effort or decreases the quality of the solution to the given task. In short, an error lessens the efficiency. These errors can affect task time and thus efficiency if they can be revoked or ignored, effectiveness if they worsen or prohibit the final solution and very likely the satisfaction of the users if their occurrence exceeds an acceptable threshold. Error rate is not part of the usability definition by DIN EN ISO 9241-11:1998, but it is the most easily observed objective measure of usability affecting all its three parts. This is why the error rate of different touchscreen interaction concepts is studied in this research.

Moreover, error rate should be a discrete usability criterion, although the ISO definition omits to name it. The efficiency of an interaction concept is affected by all the “resources” it takes to use it. Therefore, by this definition two concepts can have similar efficiency and thus usability, if it takes a user the same amount of time and resources to complete a task, although for different reasons (all other factors being equal). If one design causes the task completion time by the number of necessary steps and another causes the same task completion time by the error-proneness of the process, the error-prone one will make it harder for users to build mental models (Reason, 1990) and has worse learnability. That is why error rate should always be a discrete usability criterion to assess interaction concepts and not only seen as a metric that might influence effectiveness, efficiency, and satisfaction.

3.1.2.5 User Experience

In the last decade, the evaluation of the ergonomic quality of software and other products changed. Additional characteristics besides usability gained importance, mainly subjective attributes like e.g. visual aesthetics, elegance, modernity, perceived quality, effect on social status, and joy of use. The combination of these and other subjective attributes together with the above-mentioned usability criteria are commonly referred to as user experience (UX). An ISO definition exists: “A person's perceptions and responses that result from the use or anticipated use of a product, system or service” (DIN EN ISO 9241-210:2010). However, it is not as commonly accepted as the usability definition (Lallemand, Gronier, & Koenig, 2015; Law, Roto, Hassenzahl, Vermeeren, & Kort, 2009). There are many other definitions in use, some differing slightly (Alben, 1996; Sward & MacArthur, 2007), others significantly (Hassenzahl & Tractinsky, 2006; Norman & Nielsen; W3C, 2005). There is no common understanding or definition how usability and user experience relate to one another (McNamara & Kirakowski, 2005; McNamara & Kirakowski, 2006). User experience can be seen as part of usability, replacing or extending the satisfaction criterion. Usability can be seen as a part of the broader concept of user experience. Alternatively, none of the two is a subset of the other; both concepts only share being partly influenced by some of the same attributes of the product and the user. For this research, a specific distinction is not important. It shall only be noted that there are criteria besides efficiency and error rate that are valuable for the ergonomic evaluation of technical systems. When trying to formulate recommendations about interaction concepts that differ only slightly in efficiency and error rate, user experience criteria will be considered as well because they affect how users interact with the system and how content they are. Users will use enjoyable technical systems more, independently of task importance (Davis, Bagozzi, & Warshaw, 1992). That is why the subjective rating of user experience is part of this research.

3.1.3 Established Usability Requirements

Many publications try to describe and summarize features and design techniques that ensure good usability of technical systems. Since touchscreen devices are software-based systems, the rules and recommendations of software ergonomics apply. The three probably best-known and most frequently used sets of recommendations for high usability of software systems are the Eight Golden Rules of Interface Design by Shneiderman (Shneiderman & Plaisant, 2010), the 10 Usability Heuristics for User Interface Design by Nielsen (1995) and the dialogue principles in the ISO standard 9241 (DIN EN ISO 9241-110:2006).

Shneiderman recommends that user interfaces are consistent, offer shortcuts, feedback, closure, error handling, reversal of actions, controllability and require little effort of short-term memory. Nielsen's heuristics are very similar, but somewhat broader. He demands visibility of system status, matching of system and real world, user control and freedom, consistency and standard compliance, error prevention, recognition rather than recall, flexibility and efficiency, aesthetic and minimalist design, easy error handling, and help and documentation. The principles stated in ISO 9241 are suitability for the task, self-descriptiveness, conformity with user expectations, suitability for learning, controllability, error tolerance, suitability for individualization, clarity, discriminability, conciseness, consistency, detectability, legibility, and comprehensibility. Some of these attributes are vague, conflicting, and not applicable in all contexts. Nevertheless, they are the core building blocks for ergonomic solutions. There are established guidelines that summarize these requirements, even with special regard to work environments with critical tasks (VDI/VDE 3850-1). They have to be considered when designing touchscreen devices. Moreover, due to the special characteristics of touchscreen user interfaces, there are more design principles to be aware of (VDI/VDE 3850-2).

3.2 Special Characteristics of Touchscreen Interaction and Differences to Pointer-Based Input Devices

The following idiosyncrasies of touchscreen interaction have to be accounted for when designing the user interface. They are the main reason why solutions intended for other software systems cannot be used without modification. The resulting advantages and disadvantages have been known and described for many years, e.g. by Greenstein and Arnaut (1987). The consequences of these characteristics of touchscreens for interaction design will be shown in 4.

3.2.1 Occlusion

When the finger of the user touches an item on the screen, some part of the screen will always be occluded by the user's finger, hand or arm (see Figure 17). Thus, some of the information on the screen will be blocked from the user's view. Because of this, it is important to arrange items on the screen in a manner that no information that is important to the user at this moment will be hard to perceive. The occlusion occurring during touchscreen interaction is difficult to predict accurately because it depends on the user's anatomy, handedness, and individual motions and preferences, as well as the screen size, screen ratio and type (e.g. mobile or stationary) of the used device. The common assumption is that the finger usually approaches from below so that finger and hand will occlude most elements directly below the target. One can omit most usability problems by placing interactive elements on the lower and side edges of the screen and labels and other explanatory information above the related elements. Occlusion is a serious problem on common touchscreens because having the possibility to perceive visual feedback during all interactions is especially important on touchscreens as explained below.

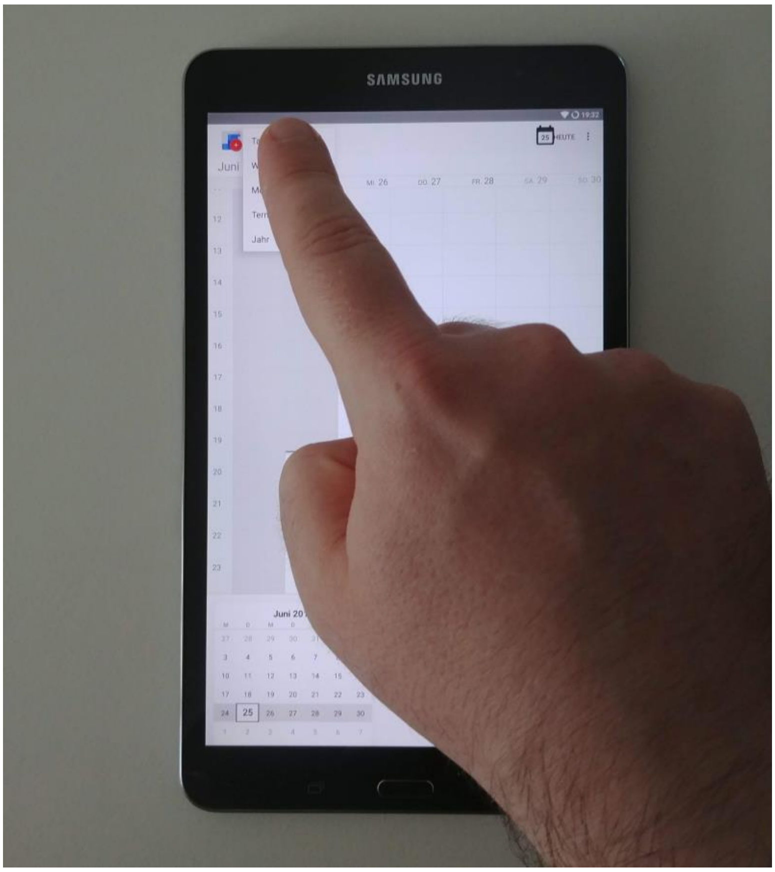

Figure 17: On a touchscreen, the users will usually occlude a considerable amount of the content on the screen with their finger, hand, and arm. The finger will even cover the very object the user is interacting with, like the dropdown menu in this example.

3.2.2 Feedback

As mentioned in 3.1.3, informing the user about successful processing and the results of the given input is a main requirement of ergonomic user interface design. Yet in contrast to other common input devices, the possibilities of giving feedback are limited in some ways with touchscreen devices. The main difference to mouse, trackball, and touchpad is the inherent lack of haptic feedback for a tap or click, the basic interaction for selection or activation and the basis for several other input commands. Since the touchscreen lacks mechanic buttons and features a solid surface, it does not give information about successful input by a change in actuation force when being pressed. Many researchers have tried to address this problem (Fukumoto & Sugimura, 2001; Jansen, Karrer, & Borchers, 2010; Kaaresoja, Brown, & Linjama, 2006; Poupyrev & Maruyama, 2003; Poupyrev, Maruyama, & Rekimoto, 2002; US

6429846 B2, 2002; Yamanaka, Uchimura, & Yamawaki, 2014). Nevertheless, all prevalent touchscreen variants lack haptic feedback, which is considered a serious problem for certain use cases, like in cars (Pitts et al., 2012). The lack of change in actuation force can be compensated to some degree with vibration actuators (Hausberger, Terzer, Enneking, Jonas, & Kim, 2017; Hoggan, Brewster, & Johnston, 2008; Koskinen, Kaaresoja, & Laitinen, 2009; Liu, 2012; Onishi, Sakajiri, Miurat, & Ono, 2013). However, they give a different sensation, may not be possible or as effective in certain solid stationary constructions and can be unperceivable if there are background vibrations, like in industrial plants or in cars (Rümelin & Butz, 2013). Auditive feedback may also be unsuitable for use cases with high background noise or potential distraction to others. Thus, touchscreen users usually have to rely only on visual feedback for asserting the successful processing and putting into action of their input commands, although multimodal feedback would increase their performance and decrease perceived task difficulty (Lee, Poliakoff, & Spence, 2009). Some researchers claim that the lack of haptic feedback can be compensated by the use of touch gestures for text input (Coskun et al., 2011; Coskun et al., 2013).

Since the visual output on touchscreens is located at the same place as the physical input, the latency of the touchscreen to display the output and its consequences for usability and acceptance have been examined by several researchers. All studies found that there is a positive impact of shorter latency (Anderson, Doherty, & Ganapathy, 2011; Deber, Jota, Forlines, & Wigdor, 2015; Ng, Lepinski, Wigdor, Sanders, & Dietz, 2012; Potter, Weldon, & Shneiderman, 1988; Sato & Nakajima, 2011). Although the experiment design and use cases of these studies differ, input latency below 50 ms seems to be a good minimal requirement for ergonomic touchscreen interaction. Kaaresoja, Hoggan, and Anttila (2011) showed that users are susceptible in a similar way to the latency of haptic feedback (vibrations) of touchscreens.

3.2.3 Precision

Like for pointer-based interaction (Card, English, & Burr, 1978), input precision has been the primary research topic for touchscreen interaction. Several researchers have studied input precision and user preference in comparison to pointer-based devices, both for button-based (Kellerer, 2010; Park & Han, 2010; Sasangohar, MacKenzie, & Scott, 2009; Sears & Shneiderman, 1991) and gesture-based touchscreen interaction concepts (Cockburn, Ahlström, & Gutwin, 2012; Forlines, Wigdor, Shen, &

Balakrishnan, 2007; Hippler et al., 2011). Their findings prove the good overall performance and user acceptance of touchscreens. The findings of Murata and Iwase (2005) and Stößel (2012) suggest that especially old people benefit from touchscreens as an alternative to pointer-based devices. Rogers, Fisk, McLaughlin, and Pak (2005) also found performance to depend on age when comparing several touchscreen interaction concepts to a rotary encoder, but only for some task. In a study using Personal Digital Assistants (PDAs) by Siek, Rogers, and Connelly (2005), precision of old people was similar to young people.

Given an ergonomic software design, the effective precision of experienced users in selecting targets on a touchscreen can be similar to other input devices like mouse or trackball (Sears & Shneiderman, 1991). In almost all use cases, items shown on a touchscreen are selected and manipulated using the user's finger. The likeliness to hit single pixels is thus influenced by the size of the user's fingertip. Since the fingertip is considerably larger than the tip of a mouse cursor and occludes the target object, the absolute input precision with a touchscreen is lower than with pointer-based input devices (Huber, 2015; Sherr, 1988). This is known as the „Fat Finger Problem" and can lead to high error rates if elements of a touchscreen user interface are designed too small (Sears & Shneiderman, 1991). It also leads to a systematic offset/error of actual touch points from their intended target (Bylund, Juhlin, & Fernaeus, 2011; Henze, Rukzio, & Boll, 2011), which is dependent on handedness (Beringer & Peterson, 1987). The Fat Finger Problem can be omitted when using a stylus with a touchscreen. However, in common use cases styluses are very rarely used because grasping them slows spontaneous interaction and they have to be secured against loss. Therefore, the size of interaction targets has a considerable influence on effective precision for common touchscreen interaction scenarios. Nevertheless, special interaction concepts like the Precision-Handle (Figure 18) can facilitate high precision input with touchscreens (Albinsson & Zhai, 2003), but they usually require users to learn them first. Since input precision is facilitated by an appropriate choice of target size, a lot of research has gone into successfully proving and assessing the impact of the size of interactive elements on user performance with touchscreens:

- Influence on performance for disabled and non-disabled people (Irwin & Sesto, 2012; Sesto, Irwin, Chen, Chourasia, & Wiegmann, 2012)
- performance during vibration (Goode, Lenné, & Salmon, 2012; Lin, Liu, Chao, & Chen, 2010; Rühmann, 1984)

- performance while driving a car (Haslbeck et al., 2011; Kim, Kwon, Heo, Lee, & Chung, 2014; Rydström, Broström, & Bengtsson, 2012)
- influence on typing performance on virtual keyboards (Kwon, Lee, & Chung, 2009; Plaisant & Sears, 1992; Sears, 1991; Sears, Revis, Swatski, Crittenden, & Shneiderman, 1993); with numeric keypads (Colle & Hiszem, 2004); on mobile devices (Karlson, 2007; Nicolau & Jorge, 2012; Parhi, Karlson, & Bederson, 2006; Park, Han, Park, & Cho, 2008; Sears & Zha, 2003); in comparison with hardware keyboards (Allen, McFarlin, & Green, 2008)

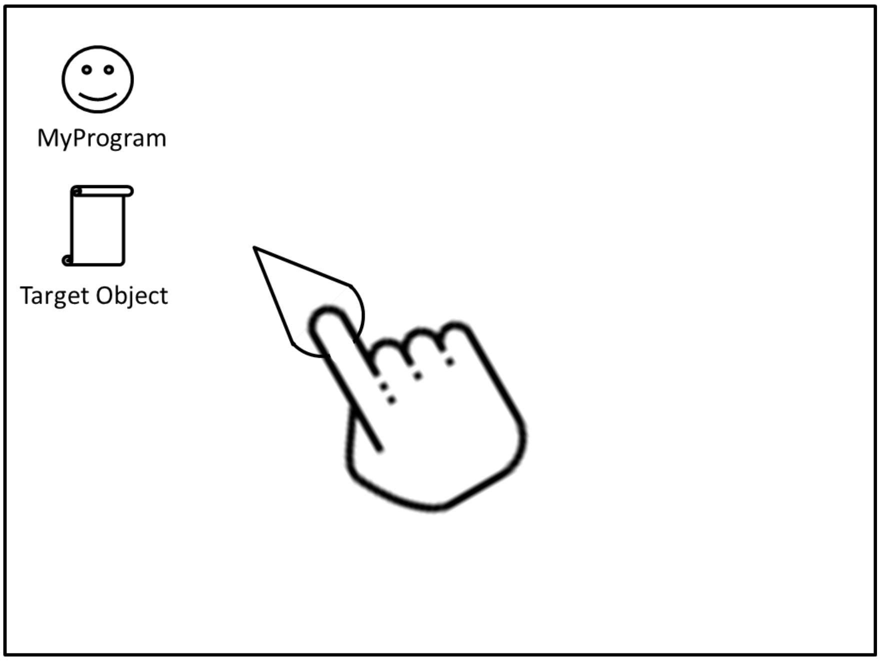

Figure 18: The Precision-Handle concept (Albinsson & Zhai, 2003) allows for high precision input on touchscreens. Instead of selecting a target with the fingertip, the user moves a target selector with narrow tip and wider bottom to point at the target.

The precision of user input can also be worsened by parallax errors (Figure 19). This means that there is a difference in the actual touch point on the surface and the intended target displayed on the screen below caused by the viewing angle and the thickness of the protective glass. This can lead to users activating an object next to the intended target object. An additional offset can stem from users using the top of their finger as visual reference, not the bottom (Holz & Baudisch, 2011).

Touchscreens are generally considered faster than pointer-based input devices for common selection tasks (Ahlström & Lenman, 1987; Sears, Plaisant, & Shneiderman, 1992) and for complex object manipulations (Hippler et al., 2011). However, they demand higher precision of users than pointer-based input devices when interacting with elements on the edges of the screen. While this is a normal selection task on touchscreens, pointer-based interaction allows moving the pointer towards the edge or corner without the need to stop before a certain point, which facilitates the motoric demand. This is why menus are always on the upper edge of the screen on some desktop operating systems like Mac OS.

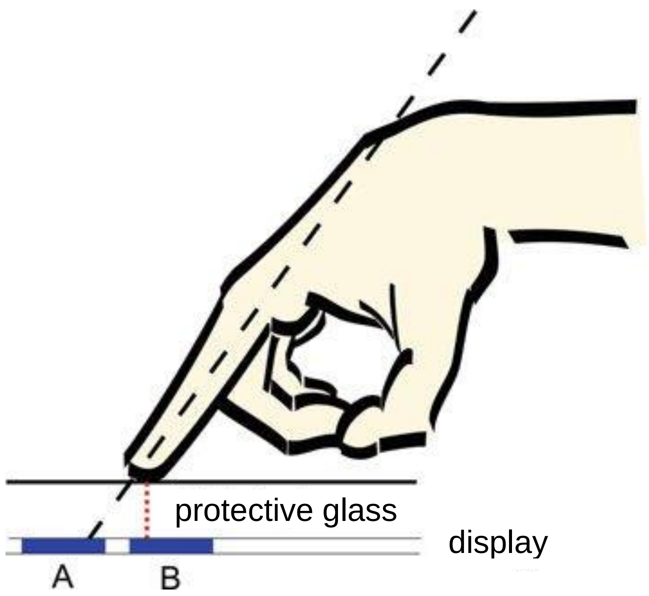

Figure 19: Touchscreen interaction can lead to parallax errors. The user targets object A, but accidentally selects item B because the touch point with the glass is lower when coming at it at an angle.

On the other hand, having the hand right where information is displayed reduces the required hand-eye-coordination for the user. That is the main reason why working with a touchscreen is easier to learn for novice users than with pointer-based devices (Arnaut & Greenstein, 1988b). With the ubiquity of both touchscreens and computer mice, this difference is arguably irrelevant today.

3.2.4 Variability

Touchscreens need almost no additional space compared to other input devices that work with software displayed on a screen. Thus, they can be integrated very flexibly in numerous devices and work conditions. Having no moving parts and being easy to encapsulate, they are predestined for adverse working conditions with high demand for ruggedness or hygiene, e.g. production or healthcare (Figure 20). This leads to a larger range of work environments where touchscreen interaction is employed. Touchscreens occur in both very large and very small devices that could not be feasibly operated with a mouse (e.g. wall display, smartphone). This has led to new challenges in interaction design and the need for extension of existing usability guidelines (Kaptan & Göktürk, 2011). While most workplaces with pointer-based devices have the operator sitting (seldom standing) at a desk or console, touchscreens are additionally operated while standing or walking freely. Because of this, the exact context of use and mode of operation is often harder to predict for touchscreen interaction than for pointer-based interaction.

Figure 20: Touchscreens are in common use in healthcare environments, partly due to their ease of cleaning and sterilization. [Source: maquet.com]

Standalone touchscreen systems often cannot satisfy all requirements of a complex workplace environment. Nevertheless, their immediate interaction and established and suitable direct manipulation concepts can improve the efficiency and user experience of common tasks for the operators. Since touchscreens need little extra space and have become easily affordable due to mass production, they will often be integrated with existing systems that offer other means of input for user convenience or safety reasons (Figure 21). These hybrid systems provide special challenges in ergonomic design: The functions offered by the touchscreen should be safe and efficient, while complementing other input possibilities consistently. When existing systems are augmented with touchscreen technology, the established processes and mental models of the users have to be taken into account as well.

On the other hand, touchscreens can also be used to replace classic desktop workstations completely. While this leads to several ergonomic challenges due to a lack of a mechanical keyboard and a relative pointing device (like a mouse), there have been both research and commercial attempts of establishing personal computers with touchscreens as the only means of interaction. Such concepts, like the Tool Space by Palleis (2017), offer a new interaction experience, mainly by relying on pervasive visual representation and direct manipulation of virtual objects. While they can be efficient and joyful to use, they particularly demand an easy-to-learn and easy-to-use design.

Figure 21: An engineer controls an industrial touchscreen system that supports direct manipulation via touch gestures. Nevertheless, the system offers a full keyboard, numerous function keys, and a trackball besides the touchscreen functionality. [Source: heidenhain.de]

3.2.5 Posture

With the exception of the rare configuration of a horizontal touchscreen with palm and arm detection (Figure 22), all touchscreens require the user to hold up the hand or arm for some time during input (Figure 23). This leads to a considerable increase in strain compared to pointer-based input where ergonomic solutions will offer some kind of support for the arm and hand. While input speed and error rate seem not to be affected by this (Schedlbauer, Pastel, & Heines, 2006), the continued strain when working for a long period of time will lead to increased fatigue and is a factor in ergonomic workplace design that has to be considered. This is especially relevant for use cases with critical tasks because they often require working while standing and over extended periods, e.g. in industrial plants or in hospitals.

Figure 22: Palm recognition, also known as palm rejection, allows users to rest their hands on a horizontal touchscreen in an attempt to reduce strain on the arms and improve input precision. It is mostly integrated in touchscreen systems that can be controlled with a stylus. [Source: https://www.robertxiao.ca/research/]

Bachynskyi, Palmas, Oulasvirta, Steimle, and Weinkauf (2015) rate both smartphones and large wall displays as unsuitable for long-term use from an ergonomic point of view. Camilleri, Malige, Fujimoto, and Rempel (2013) showed that palm rejection technology can increase productivity, but does not lead to the expected reduction of shoulder stress. The larger the display, the more likely the interactive content is out of reach of some users (Asan, Omernick, Peer, & Montague, 2011).

The variability of touchscreen use (e.g. sitting, standing, walking) requires insights about the effect of posture on input precision. According to Schedlbauer et al. (2006) touchscreens are generally well-suited for input tasks while standing, superior to trackballs. However, using touchscreens while standing requires larger interactive elements for the same precision as sitting (Chourasia, Wiegmann, Chen, Irwin, & Sesto, 2013). Ahlström, Lenman, and Marmolin (1992) assessed user fatigue based on screen inclination and showed the positive impact of elbow rests. The advantage of positioning touchscreens in the lower field of vision has been shown by Po, Fisher, and Booth (2004). Nevertheless, touchscreens that are positioned overhead can be found, e.g. in airplanes (Figure 24), which forces users into a posture uncommon for other software systems.

Figure 23: Touchscreen systems may lead to a variety of different postures for giving input. This touchscreen stand shows the common problem that users have to hold out their arm for some time when interacting. Moreover, this system will even force smaller users to reach overhead. [Source: http://www.senpallcd.com]

Figure 24: Due to easy integration, touchscreens will be integrated in a variety of places. This can lead to solutions that even require regular overhead use like this cockpit of a Gulfstream G500/G600. [Source: https://coeaerospace.com/cockpit-controls/]

Several scientists have studied the use of touchscreens during walking (Bergstrom-Lehtovirta, Oulasvirta, & Brewster, 2011; Hayes, Hooten, & Adams, 2014; Kane, Wobbrock, & Smith, 2008; Licence, Smith, McGuigan, & Earnest, 2015; MacKay, Dearman, Inkpen, & Watters, 2005; Musić & Murray-Smith, 2015; Popova-Dlugosch, Breuninger, Lemme, & Bengler, 2013). They were able to show that touchscreen use will decrease the walking speed of users. Moreover, input speed and precision significantly decrease while walking compared to standing or sitting. Thus, larger interactive touch areas are required for this use case.

3.2.6 Complexity

The interaction with touchscreens and pointer-based devices is very similar as long as it is limited to selection and activation of elements on the screen with a click or tap. However, it differs a lot for more complex interaction techniques. For pointer-based devices, the number of possible commands is easily increased with additional buttons. A click on an element with the middle, right or another additional button can trigger further functionalities related to that element. This does not even require any changes in the design of the user interface and is very easy to execute, but likewise is not self-descriptive and has to be learned by the user. Dedicated input device elements like a mouse wheel can improve the usability of certain tasks like scrolling or zooming even further while being very easy to learn.

On touchscreens, secondary functions of elements are harder to integrate in the interaction concept. This can lead to interaction concepts with low complexity for systems with limited functionality. However, it can also worsen usability compared to mouse-pointer controlled systems if a high number of complex functions needs to be accessed with this limited interaction paradigm (tap). Yet there are several possibilities to interact with a touchscreen besides tap. The most common interaction techniques besides tap are single- and multi-finger touch gestures. With touch gestures, it is possible to manipulate virtual objects in complex ways, like dragging, zooming, and rotating (see 4.2). One-finger gestures can be considered easier than their pointer-based equivalents because for those moving the pointer while simultaneously holding a button is required. Multi-finger gestures might be considered more complex than clicking additional buttons on a mouse because they require higher motoric skills. Both input methods are usually undiscoverable and have to be learned. Additionally, touch gestures require an increased effort of implementation and possibly adaption of the user interface to account for the spatial needs. How easy touch gestures are to learn and to execute depends on the user's knowledge, motoric and cognitive skill. Nevertheless, the directness and ease of learning of touchscreen gestures are considered to be the main advantage and reason of success of modern touchscreen interaction concepts (Burmester, Koller, & Höflacher, 2009; Dorau, 2011; Koller & Burmester, 2010; Saffer, 2008; Wigdor & Wixon, 2010). Clark (2011) even considers touch gestures a general successor to button-based interfaces. Thus, multi-finger touch gestures to manipulate objects can be seen as superior to alternative input methods on pointer-based devices, despite their complexity. However, it should and has been questioned if this general statement holds true for use cases with critical tasks like production environments (Friedrich, 2012; Groenefeld & Niermann, 2012; Norman & Wadia, 2013). Since multi-touch gestures can induce significant stress in the musculoskeletal system (Lozano, Jindrich, & Kahol, 2011), their suitability for work environments with continuous workload should also be scrutinized.

3.2.7 Summary

Interaction with touchscreens differs in several ways from classic pointer-based input. These differences concern the means of given input and output, as well as the environment in which touchscreens can be employed. Exploring data and interaction potential by active touch might even increase the relevance of the task and the commitment of the users (Gibson, 1962).

The differences explained above lead to different strengths of pointer-based and touchscreen interaction concepts:

- Pointer-based interaction is expedient when high information density and input precision is needed, and long-lasting continuous interaction with the software system is prevalent.
- Touchscreen interaction is suitable for quick mobile and stationary input with short periods of continuous interaction, especially for tasks that can be represented well with simply manipulable virtual objects.

4 Touchscreen Interaction Design

4.1 Basics

The basic requirements of ergonomic software design (see 3.1.3) are as valid for systems with touchscreens as they are for pointer-based systems. These requirements have been studied, documented, and applied for decades. Several standard works summarize findings and best practices. For this reason, they will not be described in this text. To find proven interaction concepts and design paradigms for interactive software, one might want to look into the works of Jacko (2012), Shneiderman and Plaisant (2010), Cooper, Reimann, Cronin, and Noessel (2014), Moggridge (2007), and Krug (2013). The following sections will focus on the peculiarities of interacting with touchscreens, which are still somewhat underrepresented or missing in most standard works on interaction design given their importance and ubiquity in today's society. The focus lies on interaction concepts that have found wide adoption after the establishment of smartphones (2007), mainly touch gestures and virtual physics. Other forms of interactions, like typing on virtual keyboards, have already been in widespread use for a longer time and are not part of this research.

Research about touchscreen interaction mainly focuses on the comparison with related input methods (mouse, touchpads, touchless gestures), technical improvements (e.g. haptic feedback), and the exploration of new interaction concepts for touchscreens. Due to the popularity and availability of these devices, the largest part of recent research is aimed at and conducted on mobile devices like smartphones and tablets.

4.1.1 Differences in Interaction Design compared to Pointer-Based Input Devices

Interaction with touchscreens differs from interaction with other input devices that are typically combined with computer screens. The most common input devices for modern human–computer interaction like mouse, trackball, or touchpad control a pointer on screen, which is part of the WIMP interaction paradigm (windows, icons, menus, pointer; see Figure 25). Modern touchscreen interaction concepts usually do not follow the WIMP design. Because of the immediate interaction with the finger, no pointer symbol is needed. Windows are mostly omitted as well because the header and borders of classic desktop GUIs are too small to grab and manipulate efficiently with the fingertip (see 3.2.3). The same is true of the menu bar; while touchscreen systems make heavy use of menus, they are usually opened via larger buttons, often marked with an icon instead of text. The representation of programs and documents as icons on a virtual desktop (desktop metaphor) is as prevalent on touchscreen systems as on pointer-based systems, mainly because the two most common mobile operation systems, Google's Android and Apple's iOS, implement their program launchers that way (see Figure 14, Figure 15, Figure 26).

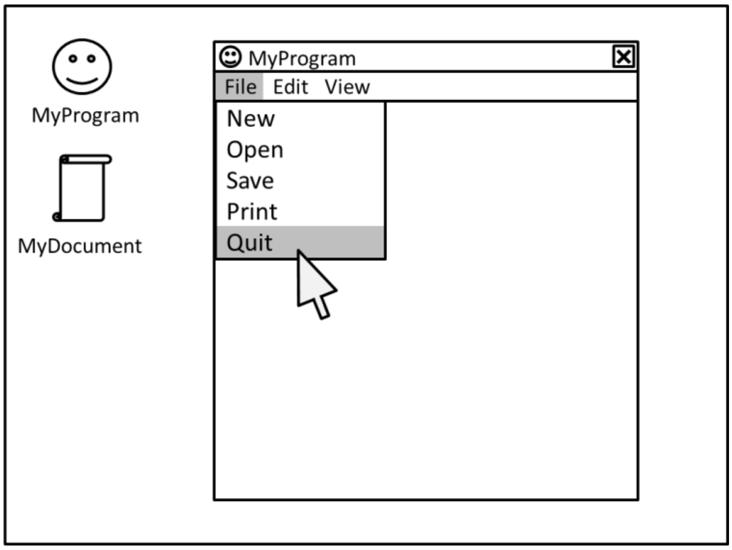

Figure 25: The WIMP interaction paradigm (Windows, Icons, Menus, Pointer). Programs and files are represented by icons. Programs open in windows. They can be controlled with menus using a pointer.

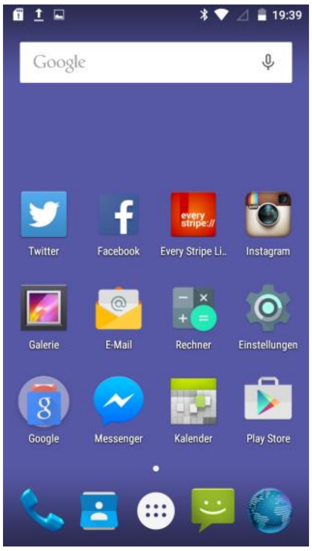

Figure 26: on an Android home screen, apps are represented as icons like on WIMP interfaces. Applications are displayed in full instead of in windows and there is no pointer symbol.

4.1.2 Models of Touchscreen Input Speed

For pointer-based devices the necessary size of targets for a certain input speed can be modelled easily with Fitts' Law (Fitts, 1954; MacKenzie, 1992). If it also applies to touchscreen interaction has often been under scrutiny from researchers with contradicting results (Bacon & Vu, 2011; Cockburn et al., 2012; Henze & Boll, 2011; Sasangohar et al., 2009; Tran, Trewin, Swart, John, & Thomas, 2013). Especially for small targets its validity has been declined and other models have been proposed (Bi, Li, & Zhai, 2013; Holz & Baudisch, 2010).

Landauer and Nachbar (1985) successfully used the Hick-Hyman Law (Seow, 2005) in their study to predict response time in menu selection using a touchscreen.

To predict the efficiency of human–computer interfaces, the GOMS (Goals, Objects, Methods, Selection rules) engineering model can be used (Card, Moran, & Newell, 1983; Gray, John, & Atwood, 1992). Abdulin (2011) has shown that its keystroke-level model is applicable to touchscreen interaction as well. If it can be applied to modern smartphones is questionable, as Holleis, Otto, Hußmann, and Schmidt (2007) have argued that there are significant differences and new interaction forms during mobile use.

4.1.3 Standards

Industry standards that document the state of the art in touchscreen interaction design unfortunately do not sufficiently cover the current knowledge and practices or discuss the whole potential and dangers of interaction concepts possible with modern technology.

The ISO standard for the design of human–computer systems, ISO 9241 "Ergonomics of Human-System Interaction", covers touchscreens relatively shortly in Part 410 "Design Criteria for Physical Input Devices" (DIN EN ISO 9241-410:2008 + A1:2012), but with little relation to real life application. Moreover, its recommendations are based on the touchscreen technology available in the 1990s. With no mention of touch gestures or mobile devices, this standard can be considered outdated.

A document that makes recommendations for touchscreen user interface design explicitly in critical tasks environments is the "Design Criteria Standard – Human Engineering" by the US Department of Defense (MIL-STD 1472). While its recommendations are still valid for many use cases, it is also too limited in scale and based on obsolete technology.

The German industry standard VDI/VDE 3850 “User-friendly Design of Useware for Machines – Part 3: Design of Dialogues for Touchscreens” (VDI/VDE 3850-3) also gives recommendations for touchscreen use in industrial use cases. However, the 2002 version of the document, which was effective when this research began, categorically advises against the use of any kind of drag-and-drop; other touch gestures are not even mentioned. This again is likely due to the technology in use at the time (e.g. small resistive touchscreens). A revised version with focus on modern touchscreen interaction has been released recently (VDI/VDE 3850-3).

4.1.4 Guidelines

When creating touchscreen user interfaces, the most comprehensive and best-known guidelines for designers and developers are those by the vendors of the technical platforms that most developers use. Given that most touchscreen devices are consumer devices like smartphones, tablets and tablet–laptop hybrids, the most relevant guidelines are by the most successful vendors in these markets: Google, Apple, and Microsoft. Each of them offers guidelines for visual design and the correct use of the available widgets on their platform (Apple Inc., 2016; Google Inc., 2015; Microsoft, 2015b). They comprehensively describe the possibilities and advantages of state-of-the-art interaction, but they are focused on consumer devices and a consistent design strategy within their platform. Some recommendations are based on technical circumstances (like size recommendations in pixels, available widgets) and not generally applicable. Other, more general guidelines omit to name concrete advantages and disadvantages of practical interaction concepts and to make applicable recommendations for real life use cases (Sears, 2009; Shneiderman & Plaisant, 2010). Others do better in that respect (Clark, 2015; Hoober, 2015, 2017; Wigdor & Wixon, 2010), but they all tend to assume favorable circumstances for touchscreen use and are therefore only partially applicable for touchscreen user interface design for critical task. Some are based on obsolete technology, e.g. Waloszek (2000). Especially for fields like the industrial sector, modern guidelines for the use of multi-touch in rigorous conditions are still missing (Norman & Wadia, 2013).

4.2 Gesture-Based Interaction

As described in 2 and 3.2.4, touchscreen interaction has been in general use for decades and its basic interaction concepts do not differ much from pointer-base devices. However, modern touchscreen technology allows interaction that is more sophisticated. The use of touch gestures can be considered state of the art in touchscreen user interface design and is part of almost all modern products. In this text, touch gestures mean lateral motions of one or more fingers on the surface of a touchscreen excluding the basic tap and motions in proximity of the screen. This means the tapping or long press of a button is not considered a touch gesture, while all swiping motions are.

The usefulness of touch gestures has been shown for many use cases, e.g. interacting with documents (Chiu, Liao, & Chen, 2011; Huang & Wang, 2011), collaboration on touch tables (Burmester et al., 2009; Dietz & Leigh, 2001; Hinrichs & Carpendale, 2011), eye-free activation while distracted (Bragdon, Nelson, Li, & Hinckley, 2011; Negulescu, Ruiz, Li, & Lank, 2012; Tinwala & MacKenzie, 2009), or user identification (Buschek, Luca, & Alt, 2015; Zezschwitz, 2016). However, their usability has also been questioned, especially for the use in cars (Kim & Song, 2014). The disadvantages of touch gestures when interacting with very large touchscreens have been studied by Zhai et al. (2013). Although people easily pick up touch gestures and find them helpful, most would not prefer tablet computers over conventional computers for their daily computing tasks (Ozok, Benson, Chakraborty, & Norcio, 2008).

These studies confirm the advantages of direct manipulation, which have been long known for pointer-based interfaces (Ahlberg, Williamson, & Shneiderman, 1992; Hutchins, Hollan, & Norman, 1985; Nielson & Olsen, 1986). The findings of Gao and Sun (2015) suggest that older people (in contrast to younger people) prefer button-based interfaces over gesture-based ones. In a study by Kobayashi et al. (2011), they preferred gesture-based interfaces. Gesture-based user interfaces can be especially helpful for people with tremor (Wacharamanotham et al., 2011). Anthony, Brown, Nias, and Tate (2013) show that touch gestures can easily be used even by young children if sufficient visual feedback is given.

4.2.1 Direct Manipulation

Touch gestures are mostly used for the direct manipulation of virtual objects. While direct manipulation on touchscreens can be interpreted as manipulating objects with the finger at the very location they are displayed, this use of the term is ambiguous because the original coining had a different meaning. The above-mentioned characteristic of touchscreen interaction will be called immediate interaction in this text.

Direct manipulation was originally defined by Shneiderman (1983, 1997), who focused on the existence of virtual objects to interact with in contrast to textual input with command languages or key sequences. This means direct manipulation is the interaction with buttons, menus, icons, marked text or other widgets (graphical interaction elements) to solve a task directly with the concerned object. It can be performed with one or more fingers or a pointer.

Buttons, menus, or tabs are sometimes not seen as part of this original definition because they are usually not the targeted object of a task, but rather an intermediary interaction concept. Modern publications sometimes refer to this as indirect manipulation (Kwon, Javed, Elmqvist, & Yi, 2011). Additionally, menus and tabs have become so ubiquitous that their visual presentation has become abstract over time and thus their initial metaphor unknown to most users (menus were originally drawers; tabs lost their office-derived styling in some implementations). As this research focuses on gesture-based interaction, the distinction is not important.

Direct manipulation can be further differentiated by the type of target and the type of manipulation (see below).

4.2.1.1 Object Manipulation

The most frequently used variant of direct manipulation is object manipulation. The object is a virtual representation of a real object or a metaphor for an action or abstract concept. Its level of detail may vary, e.g. an abstraction, like an icon, a 2D drawing, or even a 3D model (Figure 27). Depending on this, the kind of manipulation usually differs (see 4.2.1.3). Interacting with 3D models on touchscreens still lacks common standards and is an active field of research (Cohé, Dècle, & Hachet, 2011).

4.2.1.2 Plane Manipulation

Besides manipulating distinct objects, a dominant interaction form on touchscreens is moving panes, lists, and backgrounds via direct manipulation. This usually changes the visible section of a virtual plane that is larger than the screen or frame it is displayed in (Figure 28). Plane Manipulation can be one-dimensional (e.g. vertical scrolling through a document) or two-dimensional (e.g. changing the viewport on a map). A clear distinction between object manipulation and plane manipulation can sometimes be difficult: When the pages of a document are displayed with full screen width, they can be interpreted as objects moving in front of a background or as the background plane itself.

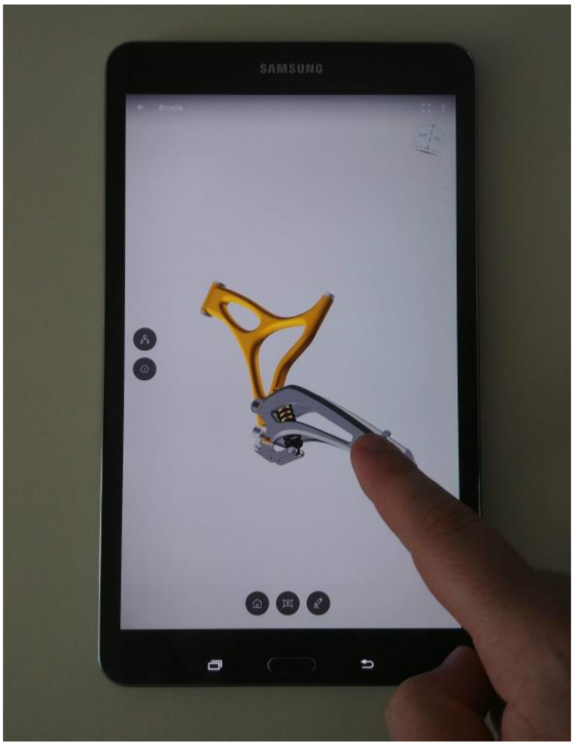

Figure 27: Object manipulation via touch gesture. These CAD bicycle parts can be rotated around the x- and y-axis with swiping touch gestures. For 3D models like this, rotation is the most common effect of such gestures. Lateral motion and zooming usually have to be realized with gestures that are more complex or with other means.

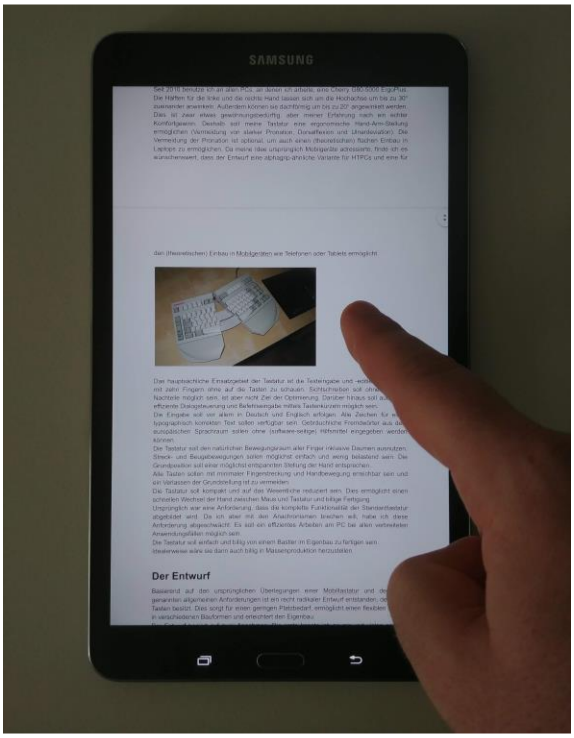

Figure 28: Plane Manipulation via touch gesture. This text document consists of several pages that are aligned vertically, but only one at a time will fit the screen. To navigate them, one drags the document background to move the pages in and out of the viewport in vertical direction.

4.2.1.3 Spatial Manipulation

The most common form is spatial manipulation of an object. It can be dragged from its original position to another position (“drag and drop”, Figure 29) by touching the object, moving the finger on the touchscreen surface (“swipe”) and raising it over the target. The movement might be two-dimensional or constrained to one-dimensional (e.g. sliders). Drag and Drop is the best-known form of spatial manipulation. On touchscreens, it is not as ubiquitous as it is on WIMP interfaces. The object and the target area are largely occluded by the user’s finger and the dragging process can be accidentally aborted early, if the friction between finger and touchscreen surface leads to rubbing that shortly interrupts detection of contact by the touch sensor.

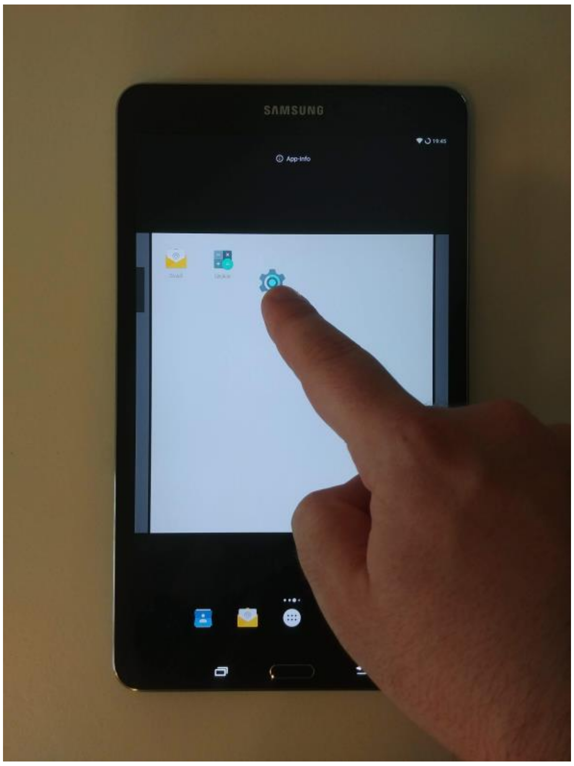

Figure 29: Spatial Manipulation via touch gesture. The user moves the gears icon to a different location on a two-dimensional grid. Depending on its size, the manipulated object is hidden from the users view to a great degree.

Alternatively, objects can be rotated instead of moved. Rotation around more than one axis requires a 3D model of some kind (see Figure 27). Given a large enough object, rotation around the z-axis (orthogonal to the display plane) can be achieved with a two-finger gesture (moving fingers around each other) while preserving the possibility to move the object with one finger.

Planes are moved the same way as objects, they usually can be “grabbed” at any location. They are only very seldom rotated around the x- and y-axis (e.g. the reference plane for a 3D model in a CAD application), but often around the z-axis with two fingers (e.g. maps).

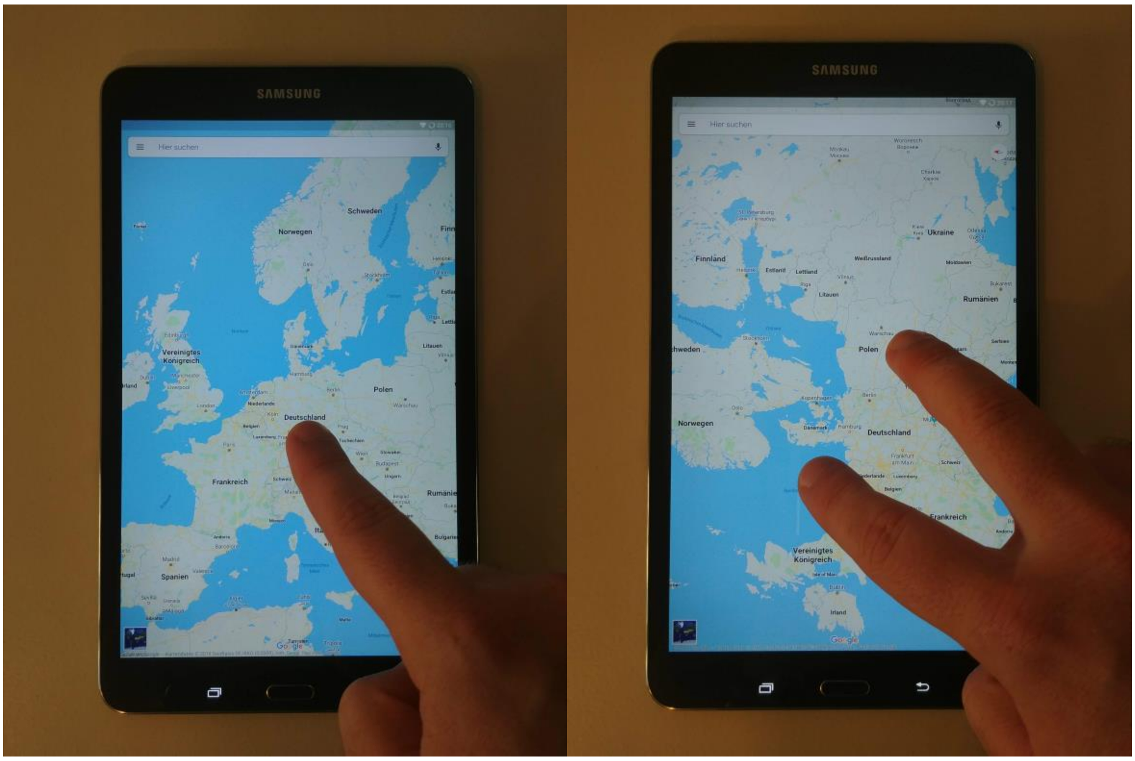

Figure 30: Spatial plane manipulation via touch gestures. Maps applications are a common use case for two-dimensional scrolling with swiping gestures (left). Moreover, some allow the map to be rotated with a two-finger gesture (right). Either one finger stays static and the other moves around it, or both fingers move on the opposite sides of the same circle with constant distance to each other. Like most two-finger gestures, this can be performed with any combination of fingers, including the thumb.

4.2.1.4 Size Manipulation

The only widely established dual-finger touch gesture is pinch and spread (Figure 31). By spreading and pinching two fingers on the touchscreen surface, the underlying object can be scaled up or down, respectively. This works just as well with virtual planes where the scaling leads to a smaller or larger region of view, which is called zooming.

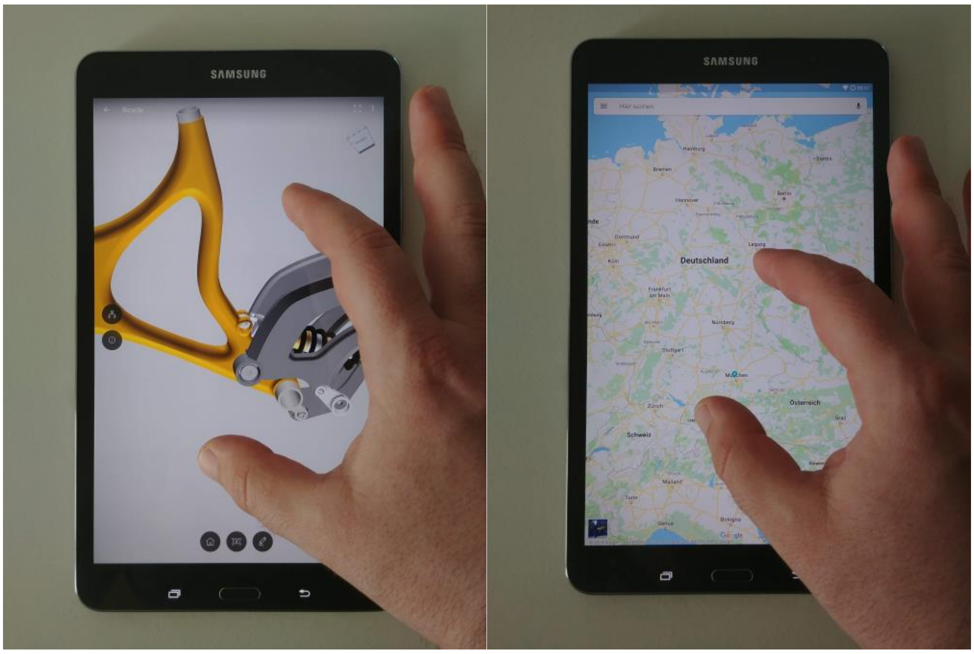

Figure 31: Size Manipulation via touch gesture. By pinching or spreading two fingers, one can both manipulate objects (left) or planes (right) in size. This can be interpreted as the size of the target or the distance of the viewer to the target changing.

4.2.1.5 Modifier (Multi-Touch Gestures)

Almost all touch gestures for one finger can by executed with two or more fingers instead to trigger (usually similar, but) different functions (Figure 32). This is equivalent to clicking on objects with one of the secondary mouse buttons.

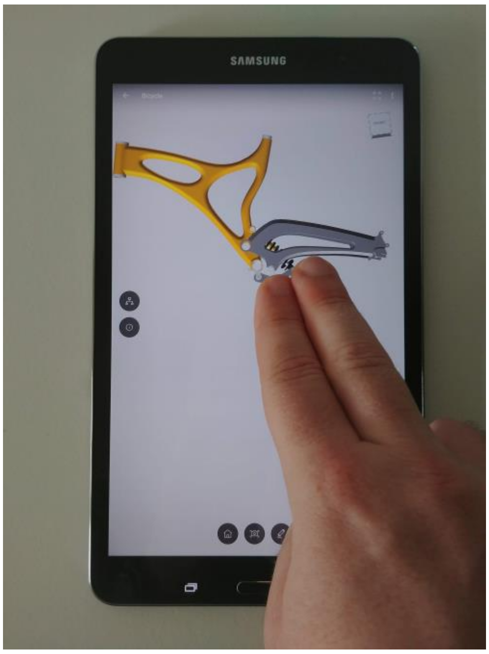

Figure 32: Manipulating an object with a two-finger touch gesture. Moving this 3D CAD part around laterally works the same way as rotating it, but with two fingers instead of one.

4.2.2 Virtual Physics

The second important characteristic of modern gesture-based touchscreen interaction besides direct manipulation is the use of virtual physics. Virtual elements of the user interface can mimic the physical behavior of real-world counterparts to improve user comprehension of the metaphor and its workings. Applying physical constraints also aims to improve efficiency or reduce error rate. The following physical properties are commonly used to achieve these goals.

4.2.2.1 Inertia

Inertia is an object's resistance to acceleration or deceleration. In touchscreen interaction, mainly the resistance to deceleration is used to allow lasting spatial manipulation of objects or planes without the need for extensive and repeated input gestures. Since an impromptu reaction to input gestures is an important requirement for efficient and satisfactory interaction, the resistance to (positive) acceleration is usually not implemented. This might be seen as an unrealistic inertial behavior. It can be interpreted as the users' manipulations being of very high force compared to the low mass of virtual objects and their grip to objects and planes being too strong to break. The best-known examples for the use of virtual inertia is the possibility to flick long lists, large map views or rotating objects into continuing motion with a quick single swipe gesture that loses contact with the touchscreen surface while the finger is still in motion.

4.2.2.2 Drag

Virtual drag is commonly applied to virtual inert objects and planes to counteract the implicit disadvantages of unconstrained inert motion. Without drag, an inert motion of a list would continue with the same speed until the end of the list is reached. The user has control over the speed of motion by adjusting the speed of the swipe gesture. Ideally, the speed is very high, but still allows recognizing and grasping the target item. Since the length of the list and the position of the target item are usually not exactly known, attaining this ideal speed is difficult. Moreover, the selection task becomes an uninterruptible monitoring task. The user has to keep track of passing items to stop the list at the right time to select the target. An object with virtual drag will stop by itself after some time, forcing the user repeatedly to choose direction and speed of another input gesture or to select the reached item. This requires more gestures, but makes the task less complex and interruptible.

4.2.2.3 Gravitation

Some widgets in touchscreen interaction concepts have to be secured against unintended activation. This is especially important because of the lack of haptic feedback, which makes unintended activation very hard to notice if the touchscreen is not in the line of sight and its visual feedback not consciously monitored. In an environment where critical tasks are controlled by touchscreens, this is even more relevant.
One way to prohibit unintended activation of widgets is to force the user to execute a distinct, usually linear touch gesture overcoming a defined threshold. This mimics an object overcoming the gravitational or magnetic force of another object. The failure to reach the threshold results in the autonomous return of the drawn object to its initial position. The best-known example of the described behavior is the “slide to unlock” widget to deactivate the lock screen on the original iPhone (Figure 33).

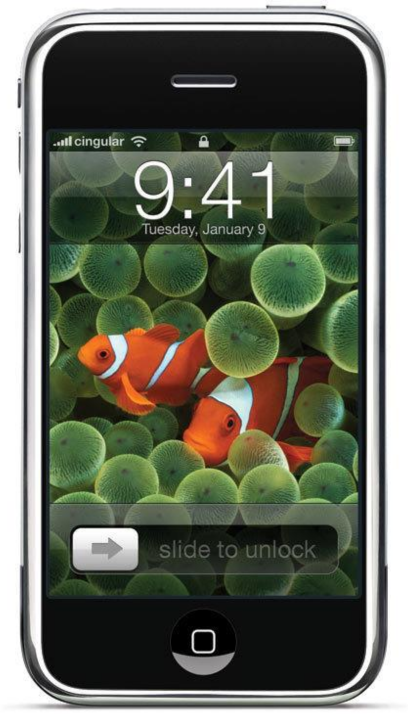

Figure 33: The unlock slider of the original iPhone. It will only unlock the phone if it is pulled far enough to the right, so that a virtual gravitation from the left is overcome. Otherwise, it will automatically return to its original position on the left. [Source: https://www.macworld.com/article/3204152/original-2007-iphone-photo-album.html]

Sometimes, the target position will exert a second, weaker gravitational force that leads to the object snapping into place when the threshold is overcome. Snapping into valid places without the need to position an object exactly is also used to improve efficiency in many common drag-and-drop tasks. The animated return to the initial position also offers good visual feedback that dropping the object at that point is no effectual command and the previous state has not changed.

4.2.2.4 Elasticity

An effect similar to gravitation is used to show the user the limits of spatial manipulation. In this case, objects cannot escape the retracting effect as if they were attached with a spring or an elastic band. They can be moved somewhat over the allowed limit, but return to the outmost valid position when released. This effect has become known as the “rubber band” or “bounce-back” and is famous for its arguable patentability by Apple (US 7469381 B2, 2008). In their devices, lists show this behavior when drawn further at the end (Figure 34).

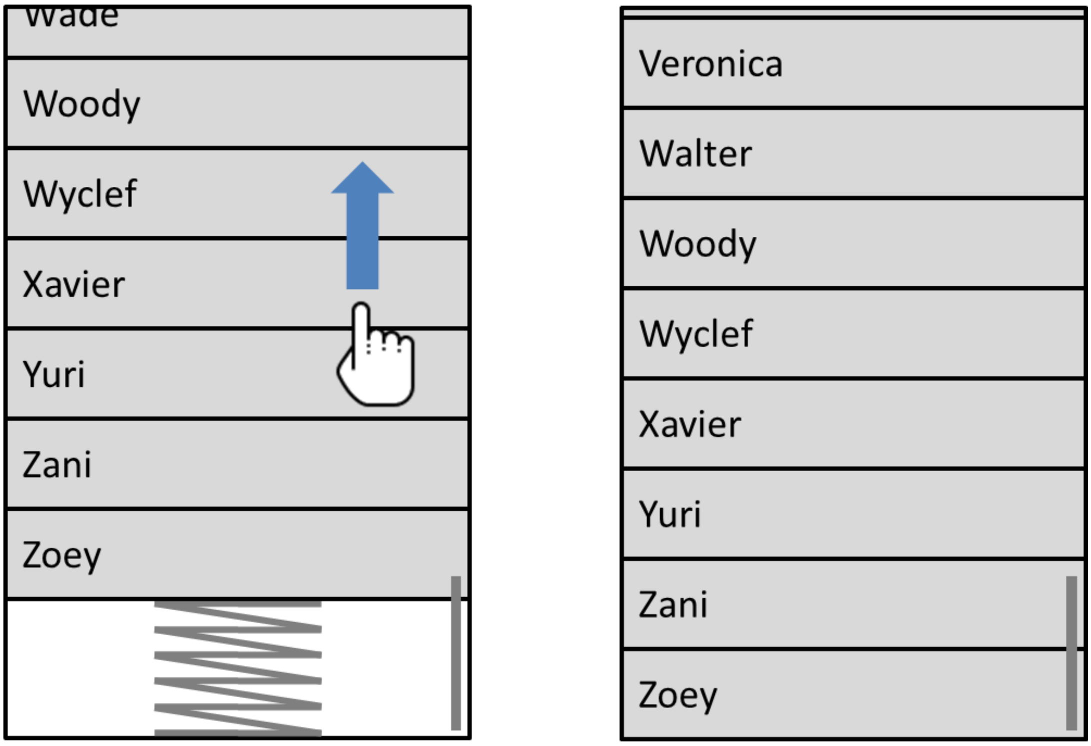

Figure 34: Elastic Scrolling: When the users scrolls to the end of a list, the scrolling will not stop when the last item is fully visible on screen, but the list will continue to move a little bit further (left) and snap back to the bottom (right) as if it was attached with a spring or a rubber band. Usually, no visual metaphor, like the spring in this example, is displayed.

Elastic behavior is useful for scrolling, at the beginning and the end of a list, as well as all other use cases where a reasonable constraint in movement of virtual objects or planes is in effect. Elastic behavior has the advantage of being an easy to understand metaphor that communicates to the users that the constraint they are experiencing exists by design and the software system is responsive and working.

4.2.3 Semantic and Symbolic Gestures

Touch gestures can not only be used to manipulate virtual objects on screen, but also to make semantic gestures, which are independent of the objects on screen and have to be memorized by the user to be applied. Semantic gestures are gestures that have a memorable coherence with the triggered function, like spreading all fingers to indicate “open” and bringing them together for “close”. Gestures as a means to interact with technical systems have been employed in different use cases (e.g. in the automotive context) and are a current field of research (Bader, 2011; Billinghurst & Buxton; Ishikawa, Horry, & Hoshino, 2005; Kühnel et al., 2011; Stecher et al., 2015). Semantic gestures for touchscreens are more limited. While there are efforts to detect hand gestures more freely (Aezinia, Wang, & Bahreyni, 2011; Wojtczuk, Binnie, Armitage, Chamberlain, & Giebeler, 2013), only two-dimensional gestures on the touchscreen surface are feasible because of the sensory abilities of common touchscreen technology. In other fields, complex three-dimensional gestures with several extremities have been employed (Lee et al., 2012; Liu, Fujii, Tateyama, Iwamoto, & Chen, 2017; Stecher, Michel, & Zimmermann, 2018).
Symbolic gestures are a special form of semantic gestures: they are similar to symbols that are related to the triggered functions (e.g. letters for text input or as initials of commands). Semantic gestures can be considered the touchscreen’s counterparts to keyboard shortcuts. Due to their lack of discoverability and the need for memorizing, they have not found widespread adoption yet. Moreover, they might interfere with direct manipulation, so they need a dedicated area for execution or a user interface without direct manipulation. An example set of semantic touch gestures is proposed in VDI/VDE 3850-3. Finger-Count is a relatively simple set of semantic touch gestures: The number of fingers used in a tap activates the corresponding menu item (Bailly, Müller, & Lecolinet, 2012).

4.2.4 Difference in Gesture-Based Interaction compared to Pointer-Based Input Devices

Gesture-based interaction exists for pointer-based input devices as well, but is used to a smaller extend there. Being its original birthplace, direct manipulation of objects is as ubiquitous in common graphical user interfaces for desktop computers as it is on touchscreens devices. Direct manipulation of planes is a lot less common however. Alternative measures for scrolling and zooming are prevalent, like dedicated widgets (scroll bar, zoom bar) or input elements (mouse wheel). The fact that the standard mode of operation of the pointer is marking elements or text makes it necessary to switch modes actively to drag planes. The pointer will usually change from an arrow to a hand in this case. Yet for some use cases like scrolling maps the predominant and expected behavior is direct manipulation without mode switch. Unfortunately, most map implementations do not show a hand by default, but the standard pointer symbol, an arrow. This makes it hard for users to predict the behavior of the system.

Commands that are implemented with multi-touch gestures on touchscreens need different interaction concepts when executed with mouse or trackball. With touchpads, many of them are possible though. Since the input is separated from the display, semantic gestures are more common than on touchscreens. For example, two-finger-swipe left or right is used for navigation or content switch.

Semantic gestures with the mouse are seldom, but used by some in use cases that are almost exclusively mouse-driven (e.g. browser gestures).

4.3 Novel Interaction Concepts

Numerous improvements in touchscreen interaction that have been proposed:

- concepts for selection with high precision (Benko, Wilson, & Baudisch, 2006; Käser, Agrawala, & Pauly, 2011; Kwon, Kim, Kim, & Han, 2010; Lee, 2010; Xu, Yu, & Shi, 2011)
- finger proximity sensing for better precision (Yang, Grossman, Irani, & Fitzmaurice, 2011)
- interaction concepts that additionally take finger angle into account (Xiao, Schwarz, & Harrison, 2015)

- interaction concepts that additionally take motion sensors into account (Hinckley & Song, 2011)
- single finger alternatives to multi-touch gestures (Olwal & Feiner, 2003; Olwal, Feiner, & Heyman, 2008)
- alternative touch gestures for scrolling (Arthur, Matic, & Ausbeck, 2008; Smith & Schraefel, 2004)
- alternative touch gestures for links (Jung & Jang, 2015)
- alternative touch gestures for menus (Bailly et al., 2012)
- alternative touch gestures for maps (Artinger et al., 2010; Artinger et al., 2011)
- concepts that facilitate interacting with small widgets (Lü & Li, 2011)
- new forms of text selecting (Roth & Turner, 2009)
- alternative forms of virtual keyboards (Go & Endo, 2008; Kienzle & Hinckley, 2013; Oney, Harrison, Ogan, & Wiese, 2013; Oulasvirta et al.; Wang, 2013).

Some of these novel interaction concepts might offer reasonable ergonomic improvements over existing solutions. However, since the goal of this research project is to come up with general recommendations for systems that are in use today, the focus lies more on known interaction concepts that can realistically be implemented with today's hardware and software and are easy to learn for novice users.

4.4 Common Usability Problems in Touchscreen Interaction Design

Many touchscreen solutions today do not fulfill basic ergonomic requirements, as described in 3.1.3. Their design frequently does not take into account the characteristics described in 3.2. They even fail to meet the fundamental principles of user interface design that apply to non-touchscreen solutions as well. The reason some of these problems frequently occur on touchscreens is the prevalent use of direct manipulation as the fundamental interaction concept.

4.4.1 Feedforward

Before a user can interact with a technical system, the possible ways of interaction have to be known and the consequences of interactions should be predictable. Therefore, the system has to communicate these possibilities to the user, on touchscreens mainly by visual design. The cues in the visual design have to be easy to comprehend by novice users and quick to recognize by recurring users. The users have to be aware of the current state of both the controlled technical system and the input system to make decisions concerning their task. The interaction possibilities of things have been denoted as “affordances” by Gibson (1979) and the term has been made popular as a design criterion (e.g. in HCI) by Norman (1988). Since it has slightly different and ambiguous meanings in their publications and Norman’s use of the term changed over time (Kaptelinin, 2014; McGrenere & Ho, 2000), the term “feedforward” will be used in this text instead. Feedforward is the sum of information a system offers to communicate its state and possible actions to the user. The quality of the feedforward, how easy it is to discover, learn, and understand is often also called discoverability or self-descriptiveness. Touchscreen interfaces show the feed-forward directly at the location of the interaction, which improves the perceptibility and is one of the reasons for the popularity of touch interfaces (Brandenburg & Backhaus, 2013). Yet modern touchscreen user interfaces often lack comprehensive feedforward, especially for complex interaction forms like multi-finger touch gestures (Derboven, Roeck, & Verstraete, 2012) (see 4.2.1.4, 4.2.1.5), but also for very common interaction forms like selecting/activating objects or manipulating planes (see 4.2.1.2). This is partly due to popular minimalistic visual design paradigms like flat design that deliberately omit visual cues to define and describe user interface elements. Other forms of feedforward that are established in some pointer-based interfaces cannot be employed on touchscreens: Without a pointer, showing additional information when the pointer hovers over an object (i.e. mouseover/quickinfo/tooltip) is not possible on common touchscreen devices (without proximity detection).

4.4.2 Feedback

From the moment users interact with a technical system, they have to get feedback if their input was acknowledged and in which way the system status has changed. This omits unnecessary or erroneous inputs and assures the relevance of the user’s actions. Feedback is necessary for the users to understand their progression in solving their problem and to learn and predict the behavior of the system for efficiency gain. This primary requirement of ergonomic human–machine system design is violated on touchscreen devices just as often as on pointer-based devices. However, as described in 3.2.2, touchscreens have a disadvantage because their primary and often only feedback channel is visual. This makes it harder for some tasks to give feedback information that can be understood intuitively. Occlusion (see 3.2.1) worsens this problem by reducing the available space for immediate visual feedback. Especially on small screens, tapping virtual objects (e.g. icons, buttons), the most common form of input, often suffers from the fact that visual changes in the manipulated object are mostly occluded by the tapping finger/thumb. Touchscreen interaction concepts tend to make use of manipulating virtual objects more often than pointer-based concepts (see 4.2). For many forms of virtual object manipulation, there are not similarly well-established and reusable standards for visual feedback as for basic button-based concepts. This might lead designers and developers to omit defining visual cues more often because they need extra time to design and implement.

While lacking visual feedback is not a problem unique to touchscreen interfaces, it is an especially severe one for them because they have to rely on visual feedback strongly to compensate for device-inherent characteristics.

4.4.3 Size of Interactive Elements

The arguably biggest usability problem primarily found on touchscreens is insufficient size of interactive elements. As described in 3.2.3, due to the common use of the fingertip, a certain minimal size of an interactive area is necessary to achieve acceptable precision when using touchscreen devices. Despite ample research (see 3.2.3) and recommendations (see 4.1.4), one will often find interaction concepts that do not adhere to these requirements. This is especially true for web content and can make touchscreen devices less usable than pointer-based ones (Budiu & Nielsen, 2010). Different size requirements apply to touchscreens compared to pointer-based interfaces (Vogel & Baudisch, 2007). The reason is that the fingertip is larger than the tip of a pointer symbol and the anticipated activation point is the occluded center of the fingertip instead of the upper left corner of the pointer symbol (usually an arrow). Since selecting small targets is already a substantial problem for pointer-based devices (Chapuis & Dragicevic, 2011), the consequences of small targets are even larger on touchscreens.

Several recommendations exist based on the available research and experience of expert practitioners (Avery, Sanquist, O'Mara, Shepard, & Donohoo, 1999; Boff & Lincoln, 1988; MIL-STD 1472; Hoober, 2013; Rühmann, 1984; Thomas, 2012; Toms & Williamson, 1998; VDI/VDE 3850-3). These recommendations differ because of different addressed use cases, required precision, and study design. Yet the majority of touchscreen user interfaces in use today fails to meet any of these requirements consequently, both in web interfaces and in native apps. This might come from the vast increase of touchscreen usage, which led to many implementations by designers and developers without decent usability knowledge. Moreover, many developers that take size issues into account create their designs based on the recommendations by the vendors of currently dominating technologic platforms like Apple, Google and Microsoft (Apple Inc., 2016; Google Inc., 2015; Hofmeester & Markiewicz, 2011; Microsoft, 2015b) (see 4.1.4). Their size recommendations tend to be smaller than the ones mentioned above. This might be because they were originally aimed at very small screens (e.g. the first iPhone screen with 3.5"), which have smaller touch area requirements for certain use cases (Parhi et al., 2006). Moreover, they have the conflicting requirement of displaying a useful amount of information. This might have led to a general acceptance of higher error rates than most researchers find acceptable. The fact that these vendors originally only targeted consumer electronics with limited impact on users' safety or efficiency makes this choice comprehensible. However, this is not satisfactory anymore because touchscreen systems by these vendors have been in use in many fields besides consumer electronics for quite some time. A general feeling of impracticability and irrelevance of large touch areas and ignorance of the vast variance of possible use cases might also have led to the discrepancy between those recommendations and usability research.

4.4.4 Compatibility

Compatibility is the property of an interaction concept to match the direction of both input to and output from a technical system to the direction of its real-world counterparts, their representations, and the users' expectations (Bubb, 1993). This means that virtual objects are oriented and manipulable in the same direction as the technical systems they represent. Indicators should move in accordance to the physical items they represent or proven rules (in short: right or up for more or higher). Norman (1988) calls these relationships mappings and warns about their negative impact on usability and ease of learning if done wrong. Compatibility issues are not exclusive to touchscreen interaction, but a common usability problem of both hardware and software systems. They appear more often in systems with elaborate indicators and controls as well as in direct manipulation systems. Since modern touchscreen interaction concepts often rely on various forms of manipulation of virtual objects, they are especially prone to compatibility issues.

A common compatibility issue on touchscreens is the confusion of moving objects and moving views (Figure 35). On pointer-based desktops, the standard for moving through content that is larger than the screen or containing frame is to scroll. Pressing arrow down, page down or mouse wheel down will lead to the content below becoming visible by moving the current content upwards out of view (analogous for content to the side). Therefore, the direction of the input matches the movement of the output: A 'down' input moves the user's view down on the content. On touchscreens on the other hand, the prevalent way to move through content is plane manipulation (see 4.2.1.2). Moving the finger upward on the content drags the content upwards, making content below visible. Again, the direction of the input can be seen as matching the movement of the output: The object, manipulated with a compatible motion, moves upward in front of the user's steady view.

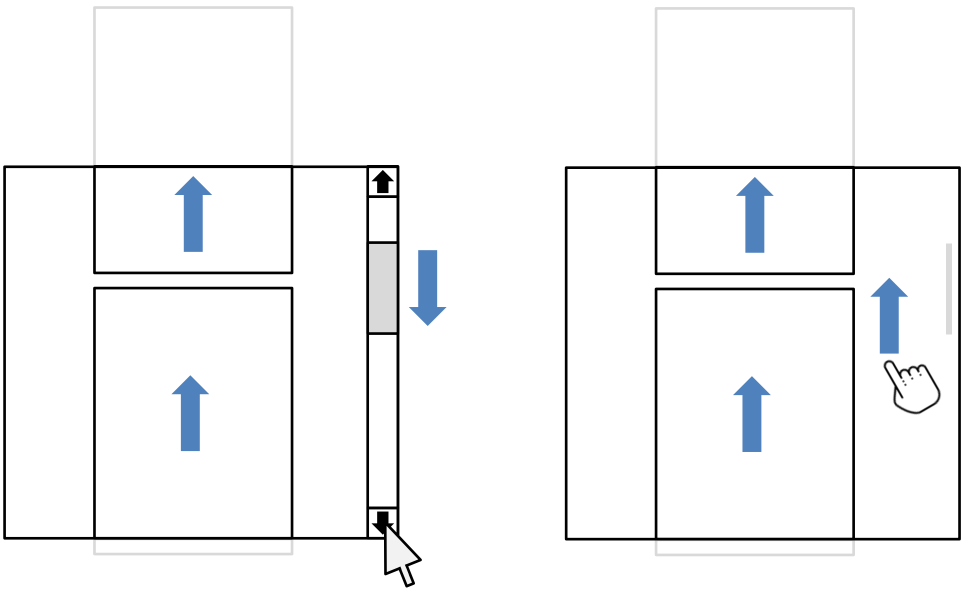

Figure 35: Common differing interaction concepts for pointer-based systems and touchscreens. To show the following pages of a document with the mouse, one moves the viewport downwards on the document with the scrollbar, the mouse wheel or the down arrow key (left). The document leaves the viewport moving upward. To achieve the same on a direct manipulation touchscreen interface, one swipes upward on the document or the background to bring the following pages into the static viewport from below (right).

This becomes a problem when users expect one behavior, but experience the other. Some touchscreen interfaces display only a position indicator instead of a scroll bar. Mouse users with little touchscreen experience might try to move this indicator, but will instead move the plane in the other direction. On some interfaces, a two finger drag works analogous to the mouse wheel leading to an incompatibility of finger and content movement. The ubiquity of touchscreens and their preference for moving objects over moving views has led to some computer vendors to changing the behavior of their touchpads from the established moving view to moving objects/planes.

4.4.5 Effects of Virtual Physics

While virtual physics effects are a well-suited model for easy-to-understand user interface concepts that offer better feedback, efficiency, and safety, they require very careful parametrization to have this useful effect. As mentioned in 4.2.2.1, inertia is usually only used to resist deceleration, not acceleration. The amount of drag should allow monitoring a moving list/plane to avoid overshooting the target without requiring too many repeated swipes. Gravitation has to be easily overcome without impeding its intended goal of improving safety against unintended activation. Most implementations of virtual physics make use of existing frameworks by the large platform vendors. Their parametrization is optimized, probably based on extensive internal research, and has proven to work satisfactory on numerous consumer electronic devices. Other implementations frequently fail to mimic this behavior, sometimes only by a small margin, which can lead to substantial deterioration of usability and user satisfaction.

4.4.6 Interference

If more than one form of direct manipulation is possible in a touchscreen user interface, inputs can be interpreted differently than intended when users execute them sloppily or recognition algorithms do not have enough flexibility to consider all applicable input patterns. This leads to input errors, which are a nuisance at best, slowing down and irritating users, or a critical safety hazard, if unintended functions are activated and users are prevented from building consistent mental models of the interface and its behavior. Common conflicts of interaction techniques are:

- Panning and zooming. Although panning is usually performed with one finger and zooming with two fingers, doing so sequentially can lead to unwanted execution of the wrong function. The combination of both techniques is very common (e.g. documents, virtual 3D-models).
- Zooming and rotating. Since both are usually performed with a two-finger gesture, activating the wrong function is likely, especially when done with one hand in a small space. Both functions are important for some common forms

of plane manipulation (e.g. maps) and therefore are often used in quick succession.

- Widgets that can be manipulated with gestures (e.g. slide switches) on scrollable planes. When there are elements on a scrollable/pannable plane that react to similar touch gestures as the surrounding area, unintended inputs are possible. This is especially the case on large/long planes where users will swipe repeatedly to scroll/pan to distant targets. These swipes can easily be executed on a passing widget where they activate unintended functions. The probability of this input error is strongly influenced by the similarity of the recognized touch gestures. While the danger is very low if the interfering gestures are orthogonal (e.g. horizontal slide switches on a vertically scrollable plane); it is very high if the interfering gestures have similar directions at one point or are even the same (e.g. rotary controls on scrollable planes, pannable map embedded in scrollable plane)
- Duration-based interaction concepts and touch gestures. As mentioned in 3.2.6, secondary functions of visual objects, which are accessed with a right-click or a combination of keypress and click on traditional WIMP interfaces, cannot be activated the same way with touchscreen user interface concepts. The most common concept for context menu and object selection/marking is the long tap (also called longpress) on the object. Both the long tap as well as the double tap can easily be executed unintendedly when meaning to execute touch gestures. The long tap might be recognized if users execute gestures too slowly, the double tap if they shortly lift a finger from the touchscreen surface due to friction or the motoric complexity. The consequence can be an unintended switch to marking mode or the opening of a context menu, which is irritating and slowing down task completion. An accidental double tap can often execute unwanted functions immediately, which might have severe unwanted consequences depending on the use case. In a critical task environment, unwanted function activation will lead to lower efficiency by taking time to correct the error; it might even put the safety of the user or a bystander into jeopardy.

5 A Model for Ergonomic Touchscreen Interaction

The following model is an attempt to structure the known and researched influencing factors of touchscreen interaction (see 3.2), as well as the influenced ergonomic qualities. Its aim is to display the current understanding of touchscreen interaction and give a basis for the discussion of pending research questions. It is based on the human–machine control loop.

5.1 The Human–Machine Control Loop

The human–machine control loop (Figure 36) is used to model interaction between humans and machines and is based on the closed/feedback control loop from control theory (Bubb & Schmidtke, 1993). It shows the interaction of human and machine when solving a task: The task is the primary input for the human, which motivates him to give input to the machine to produce a result. The result is perceived by the human as feedback, which may lead to further inputs based on the progression on the task and the characteristics of the result. Human, machine, and their interaction are influenced by the environment.

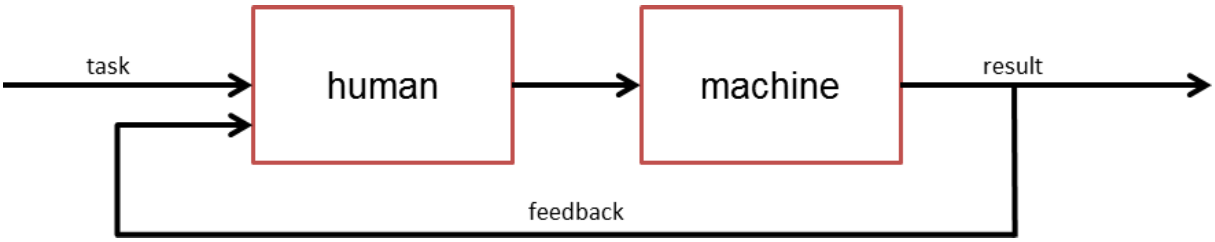

Figure 36: A simple human–machine control loop according to Bubb and Schmidtke (1993). Arrows respresent information flow. In this simple case the only way for users to assess the consequences of their actions is to observe the result that the machine produces.

If the machine is a touchscreen device, the control loop can be displayed as in Figure 37. More detail is added to emphasize the characteristics of touchscreen interaction. Since input and output are closely integrated in the device, there is an opportunity for easily perceivable feedforward to communicate system state and possible actions to the human independent of their inputs. The environment, the capabilities of the human, and design and technology of the touchscreen device influence the human–machine interaction. The primary goal of designers of human–machine interaction is to achieve the best possible result without putting unneeded strain on the human.

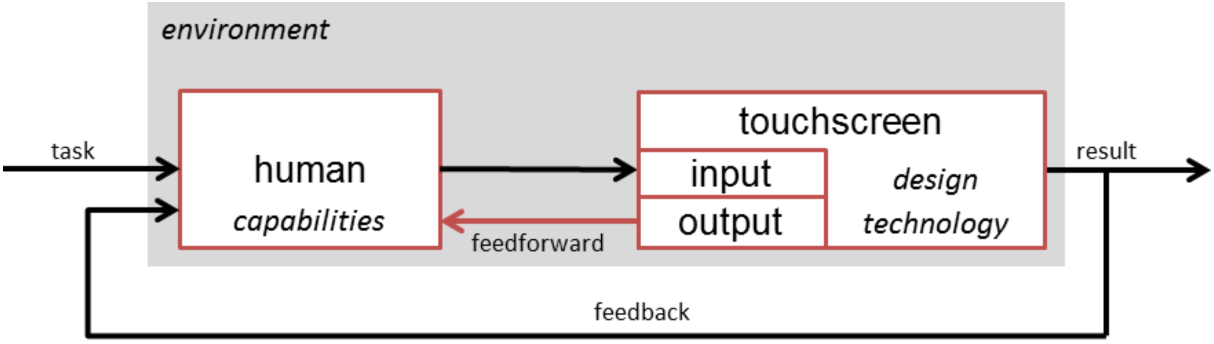

Figure 37: The human-machine control loop for touchscreen devices. Arrows represent the flow of information, italic text influencing factors. In ergonomically designed human–machine systems the machine will also give information directly to the users, e.g. about possible actions (feedforward) or to acknowledge the user's input. This requires the technical ability to give output, e.g. a touchscreen giving visual output. How well this direct output influences the human–machine system is dependent on the technology and on the individual human capabilities (e.g. sensitivity), which can be influenced by age, experience etc. Environmental factors can influence both machine and human as well as their interaction.

5.1.1 Quality of the Result

To design good human–machine interaction, one has to be able to quantify the quality of the achieved result. The following characteristics of the result and the process of working on a task can be taken as metrics to evaluate the quality of the human–machine interaction (i.e. usability, see 3.1.2):

- Effectiveness: Is the result a solution for the task? If more than one solution is possible, how well does the result solve the task?
- Efficiency: How much effort was needed to achieve the result? This includes both cognitive and physical effort, time, and other resources.
- Error rate: How many errors were made while achieving the result? Errors are activities that did not help in producing the wanted result.
- Subjective rating: How useful and how enjoyable did users find the interface when producing the result? The usefulness is a subjective assessment of the above-mentioned effectiveness, efficiency, and error rate. Enjoyableness corresponds to the concept of user experience (see 3.1.2.5).

5.1.2 Factors that Influence the Quality of the Result

There are several factors that influence the quality of human–machine interaction, as illustrated in Figure 37. Some are beyond the control of both the designers of the work environment and the machines, as well as those solving the tasks. Others can be influenced by the designer of the work environment, some by the designer of the human–machine interface, and some even by the users:

- Type of task: How complex is the task? How many elements are involved and how do they interact? Is the task static or dynamic (changes over time)?
- Environment: What external factors cognitively or physically influence the human? What factors influence the information flow between human and machine? What physical factors influence the machine?
- Human capabilities: What skills and expertise does the human have?
- Machine technology: What limitations result from the used technology?
- Human–machine interface design: How is the output of the machine designed? What is its dynamic behavior? What kind of input does it accept?

For the use of touchscreens for critical tasks, some of these factors are more important than others. The type of task can often be influenced by workplace design, but this research focuses on those use cases where it likely cannot (at least not its criticality as defined in 3.1.1). The same is true for environmental factors, which are mostly predetermined in work environments with critical tasks. Some work environments limit or prohibit the use of touchscreens (VDI/VDE 3850-3), e.g. by the use of heavy gloves or the presence of liquids or debris. While human capabilities have a substantial impact on human–machine interaction, the goal of ergonomic workplace design is to address the situations of all potential users. Ergonomic design should lead to machines and workplaces that can be used by the vast majority of people without impairment of health or comfort. The ergonomic shortcomings of certain technologies are well known, bearing many concepts for compensation (see 3.2, 4.3). The primary research focus in touchscreen interaction is therefore to evaluate different forms of input and output of interfaces concerning their impact on the quality of task completion (see 5.1.1).

5.2 Known Dependencies in the Model

Based on the research and the special requirements described in 3.2, one can name several known and assumed influences on the usability of touchscreen interaction. Although there are many factors that influence all software-based human–machine interfaces (see 3.1.3), the following examples focus on the characteristics unique to touchscreen interaction.

Performance and error rate can be influenced by the task being stationary (i.e. sitting, standing) or mobile (walking). If the task is a secondary task (e.g. while monitoring or driving), the immediate interaction on a touchscreen can be advantageous for quick perception of the output. In a dynamic two-dimensional selection task, the immediate interaction and low requirements for hand–eye coordination of touchscreens are helpful. Environmental factors that are known to influence touchscreen interaction are lighting (reflections), location, and orientation of devices (posture, fatigue, precision), vibrations (precision), and the necessity to wear gloves (precision). Human features that have been assumed to be relevant influences on touchscreen interaction are mainly age (precision), technical affinity, experience with touchscreen or similar devices (understanding, performance) and preference for mode of operation, e.g. used hand and fingers, button-based vs. gesture-based and individual differences in tap duration and pressure (performance, error rate). Technical features of touchscreens with impact on interaction are screen size (posture), surface material (friction), sensor technology (precision, error rate, working with gloves), feedback capabilities and feedback latency (performance, error rate).

When designing touchscreen user interfaces, many features have an impact on usability. Besides the common requirements for ergonomic software design, the following things are especially crucial on touchscreen devices: element placement, element size, form of direct manipulation, form of touch gestures, and form of feedback.

The influencing factors mentioned above are summarized in Figure 38.

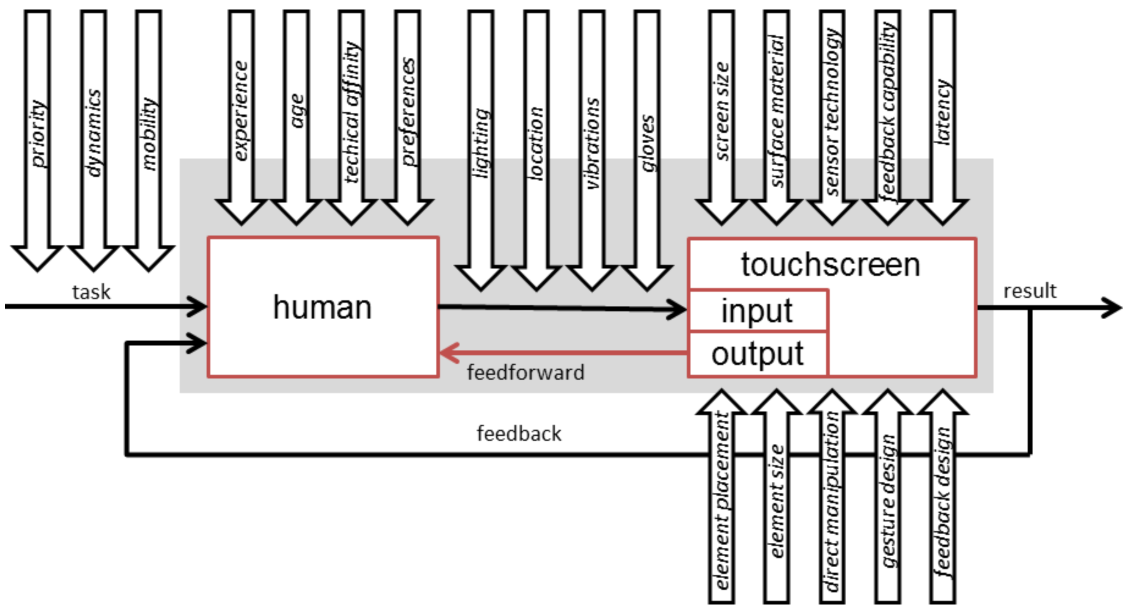

Figure 38: Factors that influence the quality of human–touchscreen interaction (wide arrows).Thin arrows represent flow of information.

6 Research Questions

6.1 Applicability of the Model to Critical Tasks

For work environments with critical tasks, all the influencing factors in 5.2 are relevant, but some more than others. Differences in task design are very relevant for work environments. The ongoing research in this area is often especially aimed at critical task environments or its findings are universal enough to be applied there. The influence of user traits and preferences on touchscreen interaction is often a secondary object of investigation in many studies. It deserves more interest. For critical task environments, insights might help to design better solutions for the realistic capabilities of all potential users. The influence of the work environment on the information flow between user and machine is arguably the best-researched field of the mentioned. It is very relevant to efficiency and error rate and has therefore been under scrutiny since touchscreens have been introduced in professional workplaces. The advancement of touchscreen technology is mostly driven by the urge to overcome the shortcomings of established technology. That is why research is often focused on the success of such improvements. These technical improvements can also render established best practices and design paradigms obsolete. For critical tasks, the advancement of feedback capability would probably be the fundamental improvement to overcome one of the most pressing problems of touchscreens.

6.2 Primary Research Interest

As mentioned in 1, there is a discrepancy between the interaction design of consumer electronics and many machines in critical task environments. The most relevant difference is the pervasive use of touch gestures and virtual physics. It is important to gain insights if these modern forms of touchscreen interaction are suitable for safety-critical environments. Without reliable recommendations based on research, either unsuitable solutions will be introduced in work environments in the coming years or a too conservative approach will hinder innovation and limit the full potential of touchscreen systems. That is why the primary goal of this research is to identify the effects of direct manipulation techniques and virtual physics, concepts that brought huge success to consumer electronics, on usability metrics that are crucial in work environments.

6.3 Further Pending Research Questions

During literature research and the conception of goals, many related questions about touchscreen interaction in critical task environments arose. It became clear that a lot more effort should go into further analyzing the peculiarities of touchscreen interaction with regard to usability under safety-critical conditions. These research questions are not part of this thesis, but show high relevance to the field of human–machine interaction. Answering them would significantly improve the ability to make general recommendations to practitioners how to design touchscreen devices and workplace environments for critical tasks.

6.3.1 Feedforward of Direct Manipulation

A major disadvantage of many direct manipulation concepts is their lack of feedforward. The visual cues for the user if and what interactions are possible are paramount to allow for ease of learning and low error rate. Yet many concepts show no feedforward at all. This is partly due to a lack of established standards in this area, as well as the current tendency to prefer minimalistic visual design paradigms. The only well-established visual cue for tappable objects is the relief metaphor (i.e. virtual shadows), which is now less common than it used to be. Shadows are also used to illustrate draggable objects (e.g. icons on the desktop) to make them appear hovering above the background; but there is even less agreement how to make the possibility of dragging objects obvious to the user. For multi-touch gestures, usually no feedforward at all is shown, e.g. the possibility to zoom with pinch and spread or rotate with two fingers. For ergonomic design of human–touchscreen interaction, it is necessary to find more and better ways of feedforward for gesture-based interaction concepts to and study their effectiveness. Moreover, with touchscreens becoming ubiquitous, it is interesting to understand which objects users expect to be manipulable with touch gestures.

6.3.2 Interference

As described in 4.4.6, interference between several possible forms of direct manipulation is a potential usability problem with severe consequences. There is ample research necessary to verify the existence of such effects, their magnitude, and the parameters of their occurrence. It would be of great use to practitioners to have a reference that explains which interaction techniques can be combined and what rules have to be applied.

6.3.3 Strain during Repeated or Continuous Use

Touchscreens in work environments may be used more frequently or for longer periods than consumer devices. While the effects of posture are well known (see 3.2.4), less knowledge is available about the influence of repeated or continuous use of touch gestures, which can be complex motoric tasks. Lozano et al. (2011) have shown that touch gestures on an iPad cause stress that may lead to musculoskeletal disorders, but more studies with different devices and focus on long-time effects for regular users have to be done.

6.3.4 Input Gain

Some of the problems that virtual physics try to address can also be addressed with disproportional input characteristics. Similar to mouse pointer acceleration, touch gesture input can be interpreted disproportionally, so that dragging a virtual object leads to a broader move of the object than the move of the finger or stylus. In this case the dragging metaphor is broken because the virtual object does not stick to the finger at all times in order to achieve greater flexibility of placement/manipulation with limited physical and motoric effort, which can lead to better efficiency. This may come at the cost of higher error rate and learning effort and lower acceptance. A study about the effectiveness of this control-to-display gain has been done by Kwon, Choi, and Chung (2011). ThumbSpace by Karlson and Bederson (2007) is an interaction concept that uses input gain to restrict the touch interaction to a space that is easy to reach with the thumb. The advantage of input gain has also been shown for graphics tablets by Arnaut and Greenstein (1988a), but further research is needed to assess speed gains, error rates and the practicality for critical task environments.

6.4 Hypotheses

Based on the characteristics in 3.2, the problems in 4.4, and the considerations in 5.2 and in 6, the hypotheses described below were chosen for this research. The primary focus was the influence of touch gestures on the usability and user experience of touchscreen interaction. Since the ergonomic quality of an interaction concept is influenced by various important factors (see 5.1 and 5.2), a general statement like “(all) gesture-based interaction leads to more errors than (all) tab-based interaction" is very unlikely to be true and impossible to prove experimentally. Therefore, the hypotheses are formulated in a way that can be proven in experiments with well-performing, ergonomic representatives of the relevant feature:

1a. The fastest gesture-based interaction concept achieves slower task completion than the fastest tap-based one.
1b. The least error-prone tap-based interaction concept has a lower error rate than the least error-prone gesture-based one.
1c. The most popular gesture-based interaction concept is rated more favorably by users than the most popular tap-based one.

Hypothesis 1c was chosen as an additional research interest because it is easy to integrate into an experiment design that addresses the other hypotheses. The user experience with an interaction concept in a critical task environment should not be the primary factor in choosing an ergonomic solution. Nevertheless, it was expected that interaction variants might differ little in task completion time and error rate. Under those circumstances, differences in user experience can become the deciding factor to choose the most ergonomic solution even for a use case in a critical task environment.

For use cases where interaction concepts with virtual physics had been established, the influence of virtual physics on usability, particularly on efficiency and error rate, was a secondary object of investigation:

2a. The fastest direct manipulation concept with virtual inertia has faster task completion than the fastest one without.
2b. The least overshooting direct manipulation concept without virtual inertia leads to less overshoots than the least overshooting one with inertia.
2c. The least error-prone direct manipulation concept without virtual inertia has a lower error rate than the least error-prone one with inertia.

For user cases where interaction concepts with continuous display of content are common, a possible advantage of paged content in terms of efficiency and error rate was also a secondary object of investigation:

3a. The fastest interaction concept with paged content has faster task completion than the fastest continuous concept.
3b. The least error-prone interaction concept with paged content has a lower error rate than the least error-prone continuous concept.

The Hypotheses 1 were to be tested in several use cases to find out if comprehensive recommendations could be made for certain design paradigms. Yet it was expected that experiments might show strong dependency on experiment design and be only valid for the studied use case. To assure the relevance of the recommendations nonetheless, experiment design focused on common use cases. Hypotheses 2 and 3 are more confined to the use case of scrolling through content. Thus, the analysis of these hypotheses was limited to a single experiment that represented this use case (see 7.8; additional conclusions on hypothesis 3 can be drawn from 7.9).

7 Experiments

7.1 Considerations on Experiment Design

When defining a hypothesis for a research question, the studied variables should be as isolated as possible to avoid confounding. To isolate variables in a study design, as many properties of the study as possible are kept constant for high internal validity. For best control over variables and repeatability, a laboratory environment is often chosen. This bears a trade-off because the more controlled a study design is the less external validity it usually has (Bortz & Döring, 2002).

To study direct manipulation and virtual physics in critical tasks, it seemed feasible to use a laboratory environment with random participants. This is expected to generate knowledge that is applicable for a wide range of use cases, as long as the task design is representative of real-world applications.

To ensure realistic study design and the relevance of the studied impact factors for companies, use cases of several companies were taken into account (Breuninger, Popova-Dlugosch, & Bengler, 2012). Relevant functions in order of importance were:

1. Navigating in dialogs
2. Monitoring and changing numeric values
3. Monitoring and changing system state, mostly represented by text or symbols
4. Monitoring and changing large amounts of data in lists or tables

The goal was to identify properties of modern touchscreen interaction concepts with direct manipulation and virtual physics that constitute reasonable variants for the independent variable in an experiment. Their effect on the metrics relevant to critical tasks, efficiency and error rate, were to be investigated. To assure the validity and the transferability of the results, the variations of the independent variable had to be realistic interaction concepts that address the four use cases mentioned above in different experiments. The focus was on established forms of interaction. Novel interaction concepts were only included in experiments if they were deemed feasible to implement in real scenarios and based on known forms of interaction. This excluded uncommon touch gestures. It was accepted that concepts allowed for several forms of interaction. A stronger isolation of touch techniques without realistic context would have led to results with little external validity. The compared interaction paradigms were tab-based vs. gesture-based input techniques, as well as virtual physics vs. no virtual physics. Since an influence of the visual form of the interaction concepts on subjective evaluation was expected (Tractinsky, Katz, & Ikar, 2000), difference in visual design had to be as little as possible. For each experiment, variants were chosen that represent an interaction paradigm as good as possible while being powerful and versatile enough for real use.

7.2 Overview

To analyze the hypotheses in 6.4 and develop general recommendations for touchscreen interface design, several usability studies were conducted. They addressed different use cases that had been observed in real world application or were of great interest to industry partners (see 7.1 and Breuninger et al., 2012). Each experiment focused on one elemental interaction type that can be approached with different interaction concepts, e.g. scrolling, function selection, navigating dialogs. This chapter will give an overview over all conducted experiments. The experiments for conscious activation (7.3) and the smart home demonstrator app (7.7) were not meant to investigate the hypotheses of 6.4, but to gain general insights in touchscreen interaction and confirm established best practices or findings from other experiments. For the experiments for menus (7.4), function selectors (7.5), and numerical input (7.6), only the key observations will be presented for one or more of the following reasons:

- Their results lacked statistically significant differences between variants to prove or disprove the hypotheses.
- They produced incomplete or faulty data due to errors in the implementation or execution of the experiment.
- The experiment design turned out to be unsuitable to prove or disprove the hypotheses without doubt, because factors besides the independent variable (variants) could have influenced the dependent variables (task time, error rate).

A deeper analysis of the results is shown for the most successful experiments: List scrolling (7.8) and horizontal content change (7.9).

7.3 Conscious Activation

Enslin (2012) studied different interaction concepts for touchscreens that have high safety against accidental activation. The best-known example of these is the slider with virtual gravitation that locks the original iPhone ("slide to unlock", Figure 33). This was triggered by the high demand from industry partners to have scientifically proven recommendations for these interaction concepts because accidental activation is seen as one of the main risks of using touchscreens in industrial environments.

Five variants (Figure 39) were implemented: Two-button activation, global unlock button, gesture-activated turn knob, slider, and pattern unlock. They were assessed by eight usability experts from the Chair of Ergonomics, a UX design agency, and a mechatronics/software engineering agency. The experts rated the concepts' feedforward, comfort of interaction, prevention of accidental activation, prevention of activation without looking, and space requirement. According to their judgement, all presented variants succeed in preventing accidental activation well. The variant with the best overall rating is the slider, which has no relevant drawbacks and which is already well established in consumer electronic devices for this use case. All other variants were rated worse, mainly due to lacking feedforward and limited comfort during interaction. Especially the turn-knob was criticized because it had to be turned with a two-finger gesture, which is very hard for users to anticipate or find out. The turn-knob and the pattern unlock can also only be used in a limited number of use cases due to their space requirement.

While this study lacked any quantitative data to get a deeper understanding of efficiency or error rates of the variants, it showed that there are numerous ways of effectively preventing accidental activation on touchscreens. This is still a common fear that prevents touchscreen usage in some critical task environments. Based on these experts' opinion, well-designed touchscreen interaction concepts like the slider-to-unlock will not have any disadvantages in terms of error rate compared to conventional alternatives. Since these interactions concepts to prevent accidental activation are usually needed only at certain points of a software system, their impact on overall efficiency is negligible.

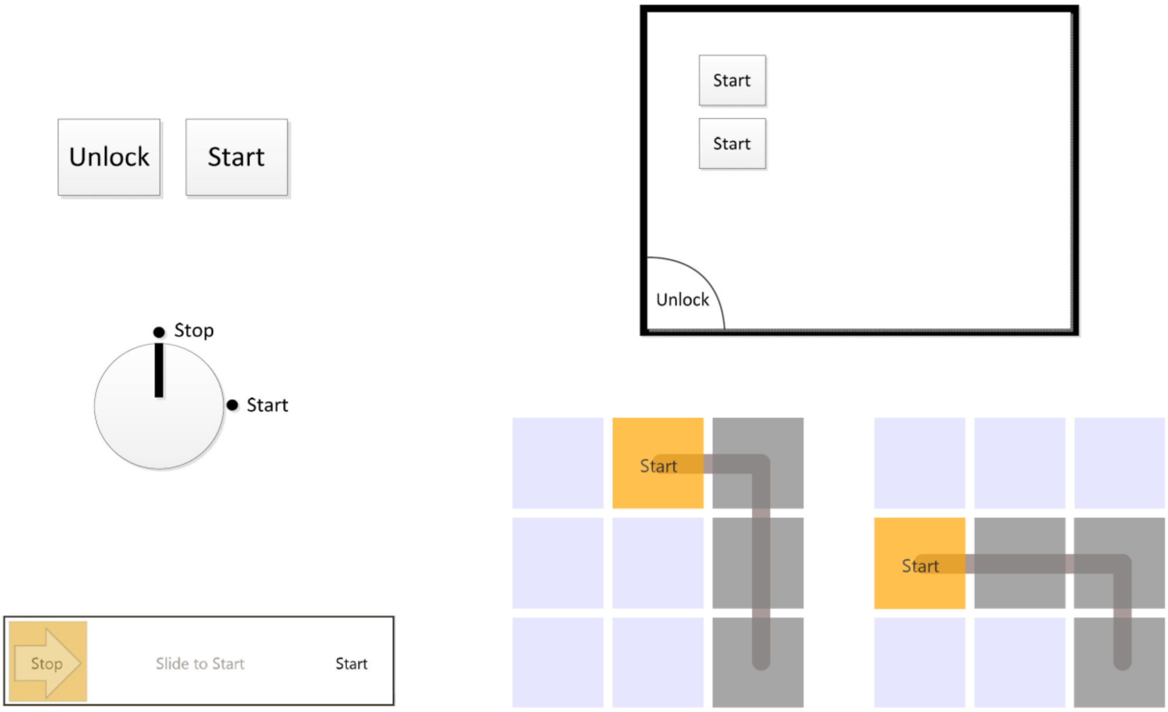

Figure 39: These variants were implemented and assessed by usability experts as means of omitting accidental function triggering on touchscreens: Two button activation (upper left), global unlock button (upper right), gesture-activated turn knob (middle left), slider (bottom left), pattern unlock (bottom right) [Source: Enslin, 2012]

7.4 Menus

Šahinagić, Bauereiß, and Mahmuzić (2013) explored and evaluated several novel interaction concepts for structured data, i.e. menus that can be used to activate functions or navigate in dialogs (Figure 40). The goal was to evaluate if any variant might offer advantages over the established and ubiquitous dropdown menu. All novel variants support touch gestures, either to scroll or to extend further levels of the menu.

All variants perform very similarly in terms of total task time, the time a participant needs to successfully locate and activate an item in the menu. Only the Cover Flow menu, a two-dimensional variation of Apple's one-dimensional Cover Flow widget, performs notably worse than the other variants. As it was the only variant that forced users to employ touch gestures and had the slowest task completion, hypothesis 1a might be accepted for this use case. However, variants that can be used with either taps or touch gestures have the fastest variant among them, the Tree menu. On the other hand, participants used them far more often with taps than with touch gestures. Because the visual presentation of the menu items might have influenced (search) task completion time, the findings remain inconclusive.

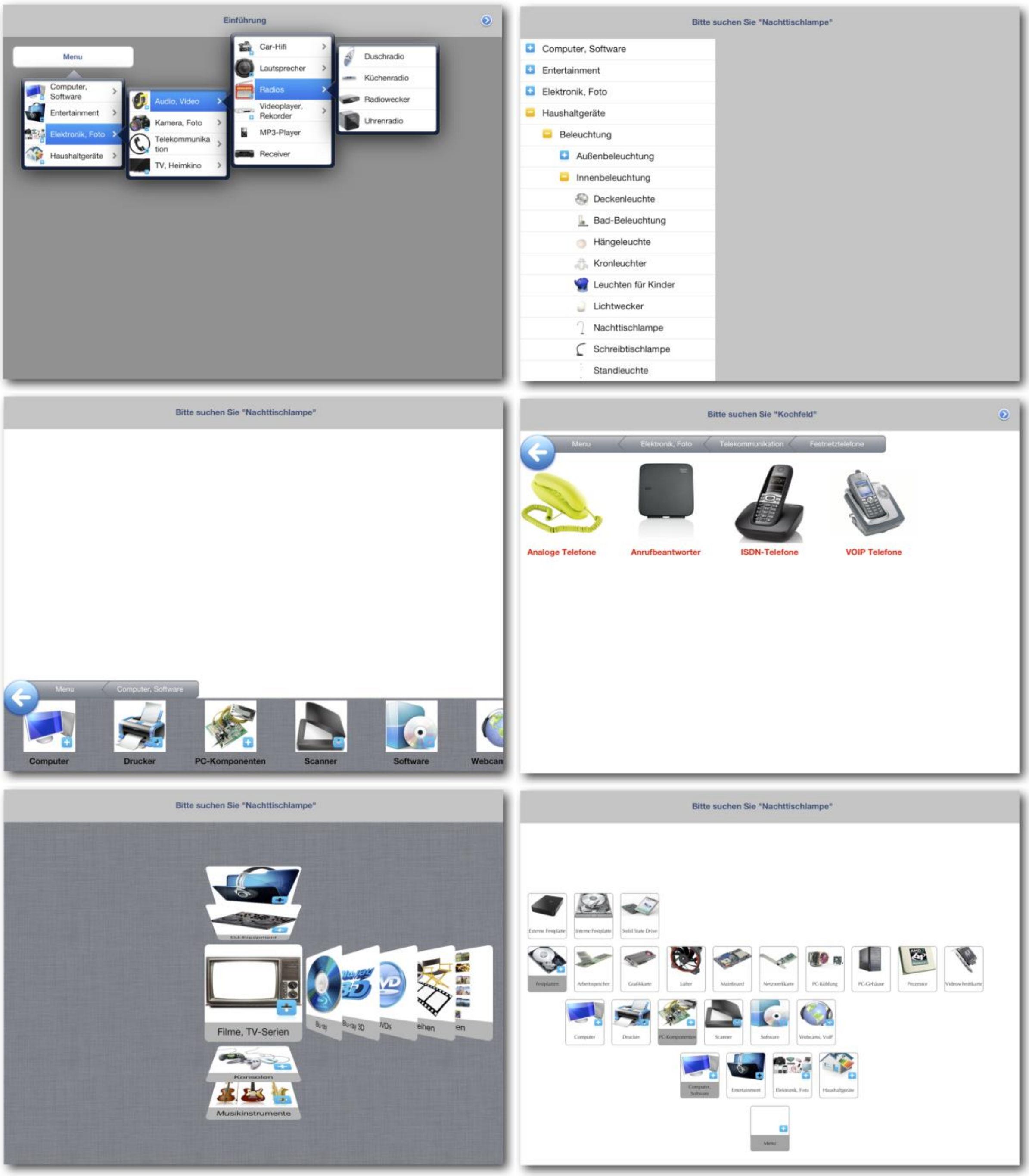

Figure 40: Six variants of novel menu concepts for touchscreen interaction, clockwise from top left: cascading dropdown, unfolding list, grid, tree, Cover Flow, and horizontal list [Source: Šahinagić et al., 2013]

The differences in observed performance are coherent with the participants' preference, where the tree variant comes first and Cover Flow comes last. The tree variant is similar to a cascading dropdown menu, but extends from bottom up, omitting the occlusion problem of touchscreens and offering more space for graphic representations of the menu items. Since it is not necessary to lift the finger to extend the next menu level, trained users can control this widget swiftly with a single touch gesture when they have learned the menu structure. This is an advantage over similar, but dynamic concepts like Rush, presented by Baur, Boring, and Butz (2010).

Due to the experiment design, there is no quantitative data of the error rate of the different variants, but video analysis revealed no relevant difference between the five variants excluding Cover Flow. Given the good UX ratings of these variants and under the premise to use menus for navigation and non-critical functions, they seem good alternatives to the standard dropdown menu, even for critical task environments. Since three variants that support touch gestures have better UX ratings than the dropdown, hypothesis 1c is accepted for this use case. The very low UX rating of the Cover Flow menu is irrelevant because it clearly stems from its low usability and thus disqualifies Cover Flow menu as an ergonomic variant.

7.5 Function Selectors

Ten different touchscreen interaction concepts for function selectors (Figure 41) were created and implemented by Hirmer (2013). In this experiment, variants that do not require touch gestures perform better overall in terms of task time and subjective user rating (Radio Buttons, Static Horizontal Selector, Tab Bar, Dial). Variants that can be used with either touch-gestures or tap are almost exclusively used with tap because participants would not discover the possibility of touch gestures (Static Horizontal Selector, Dial). Variants with insufficient feedforward, like the Pie Menu Selector and the Pinch–Spread Selector, show a considerably higher error rate than other variants due to the participants trying to figure out how they work (all ineffective input attempts were considered errors). These two variants, as well as the Pop Up, show a learning effect: Input speed is considerably lower and thus comparable to the other variants in the second and third task of the experiment. Participants rated the variants' suitability for a safety-critical environment: Only the variants that are only tap-based or optionally tap-based achieve an acceptable suitability in the participants' eyes: Pop Up, Radio Buttons, Static Horizontal Selector, and the Dial. The variants that have to be used with touch gestures, Cover Flow, 2D-Cover-Flow, the Dial Picker, and the Pie Menu Selector are rated lower. Apart from being used with touch gestures, they also show fewer functions at the same time. Therefore, their efficiency is probably lessened by the more complex search task a user has to go through. This might also influence user ratings.

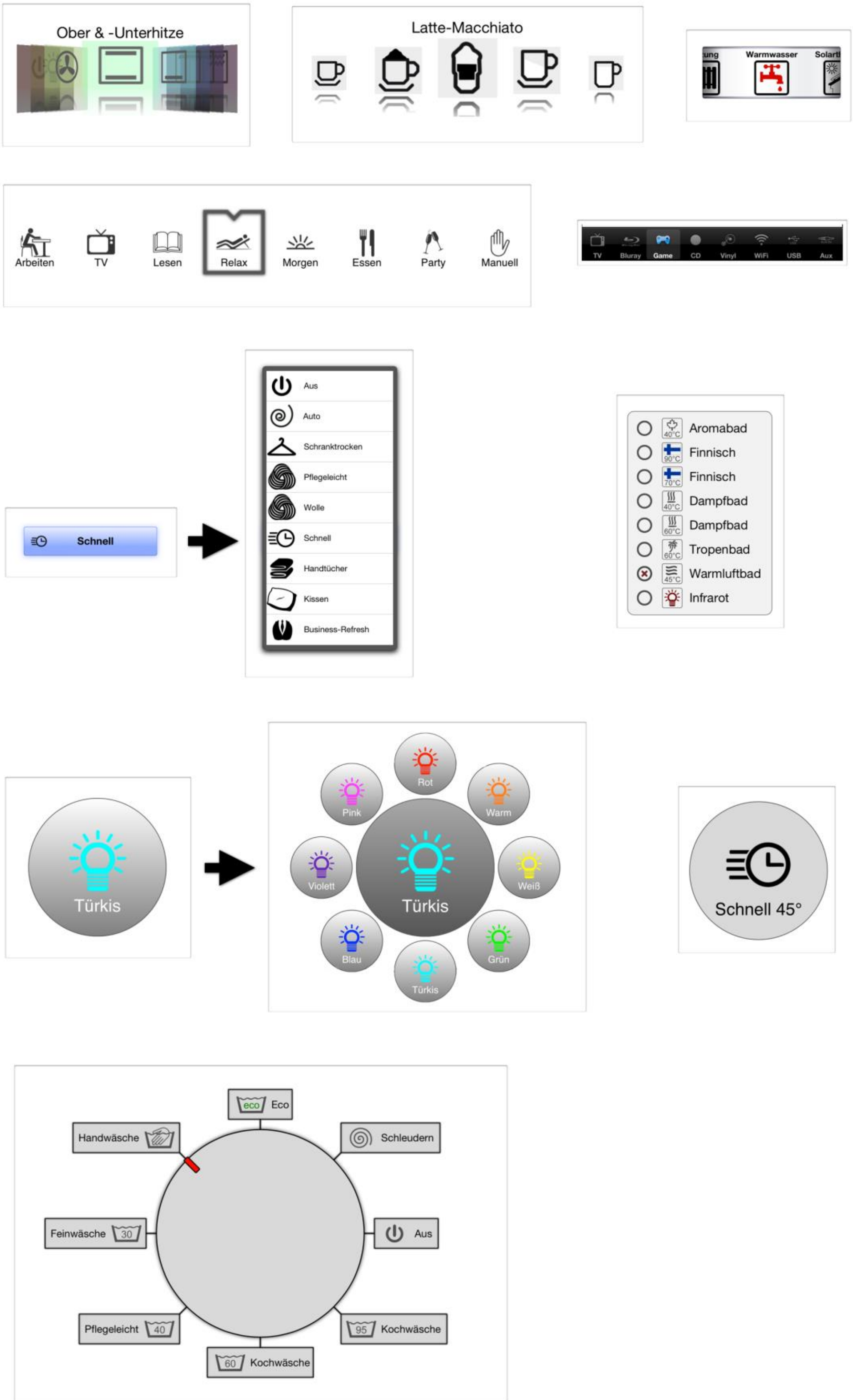

Figure 41: The selectors that were compared in Hirmer's experiment: Cover Flow, 2D-Cover-Flow, Dial Picker (top row left to right); Static Horizontal Selector, Tab Bar (second row); Pop Up, Radio Buttons (third row); Pie Menu Selector, Pinch–Spread Selector (fourth row); Dial [Source: Hirmer, 2013]

7.6 Numerical Input

Several interaction concepts for numerical input were compared in an experiment by Schelo (2013). The variants are shown in Figure 42. None of the variants led to incorrect data input and only the lever and the pinch–spread manipulator led to users employing unproductive touch gestures. These failed input attempts can also be considered errors. The pinch–spread manipulator showed four times as many errors as the lever. These results confirmed the expectations because these two variants were the least known of all and especially the pinch–spread manipulator lacks sufficient feedforward for anticipating its workings before first use.

All interaction concepts that required the use of touch gestures introduced the problem of a need for high fine motor skills to reach the correct numerical target value without overshooting. This problem could be observed with all those variants in the experiment. However, the jog wheel and the horizontal wheel showed almost half as many overshoots in total as the horizontal slider, the percentage wheel, the pinch–spread manipulator, and the lever.

Users considered the number pad the most suitable variant for use in safety-critical environments. Plus-minus-buttons, digit manipulator wheel, jog wheel, horizontal slider, and digit manipulator were also considered suitable to a lesser extent.

There were considerable differences in input speed between variants and a high variance between participants. The digit manipulator, the number pad, and the digit manipulator wheel had the fastest input speed. The lever and the pinch–spread manipulator again came last; the pinch–spread manipulator showed by far the longest total task time, but also a very high variance between participants.

In summary, the experiment showed that established interaction concepts for numerical input, like the number pad and the digit manipulator wheel, are well suited for critical task environments. They offer high input speed, neglectable error rate and are rated favorable by users. Nevertheless, lesser-known alternatives like the digit manipulator perform equally well. However, novel concepts like the lever and especially the pinch–spread manipulator cannot be considered sufficiently ergonomic based on these findings and are not recommended for critical task environments.

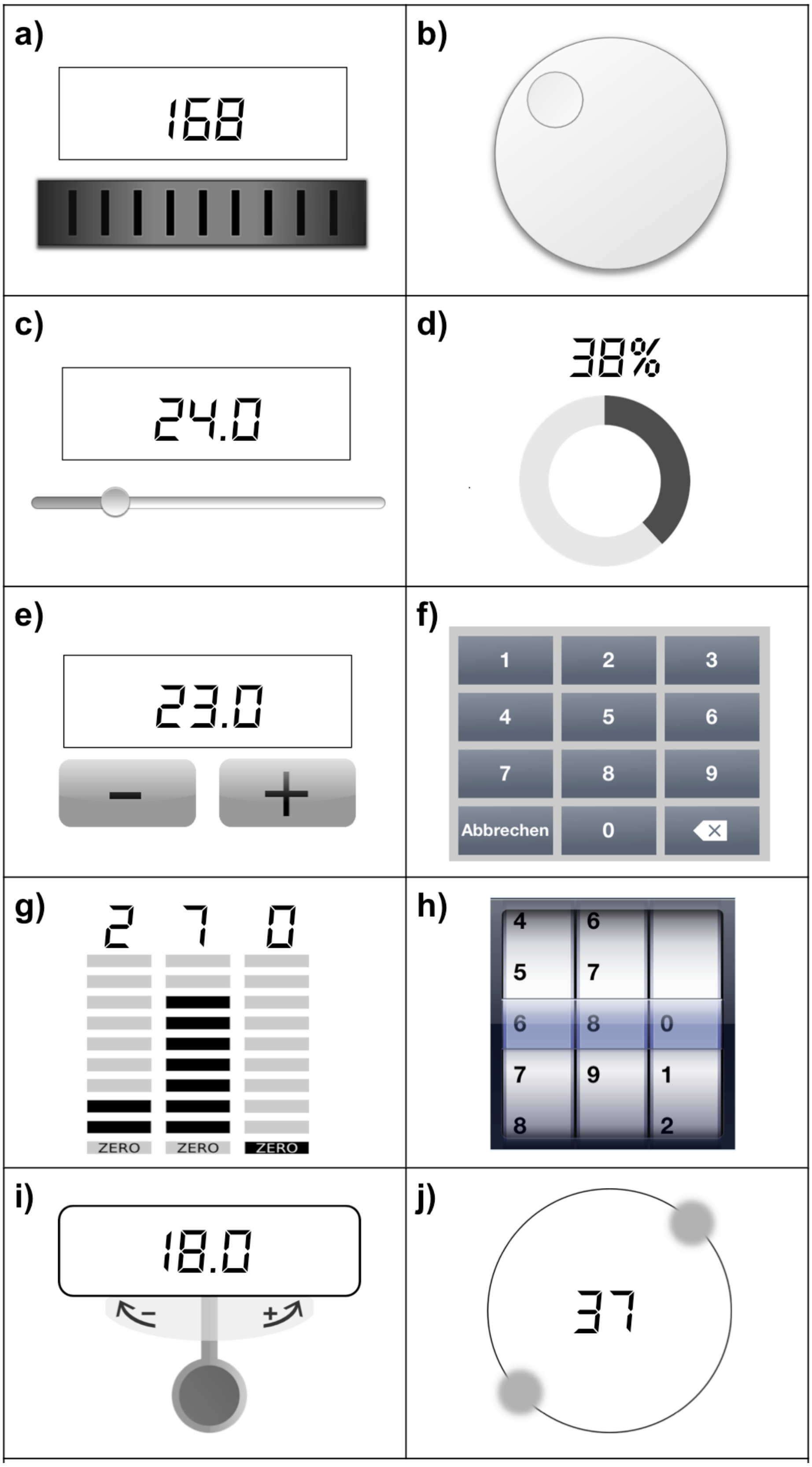

Figure 42: Different interaction concepts for numerical input on touchscreens: Horizontal wheel (a), jog wheel (b), horizontal slider (c), percentage wheel (d), plus-minus-button (e), number pad (f), digit manipulator (g), digit manipulator wheel (h), lever (i), pinch–spread manipulator (j). All variants except e) and f) can be used with touch gestures, some optionally. [Source: Schelo, 2013]

7.7 Smart Home Control Demonstrator

Hüfner and Lange (2013) designed and implemented a demonstrator app for a smart home control on an Apple iPad. They integrated several interaction concepts that had shown good results in the studies mentioned in this chapter. This integration in an app aimed to confirm the suitability of the interaction concepts in a more realistic usage scenario. The interaction design was rated very favorably in an expert evaluation, which reaffirmed the findings of the other experiments.

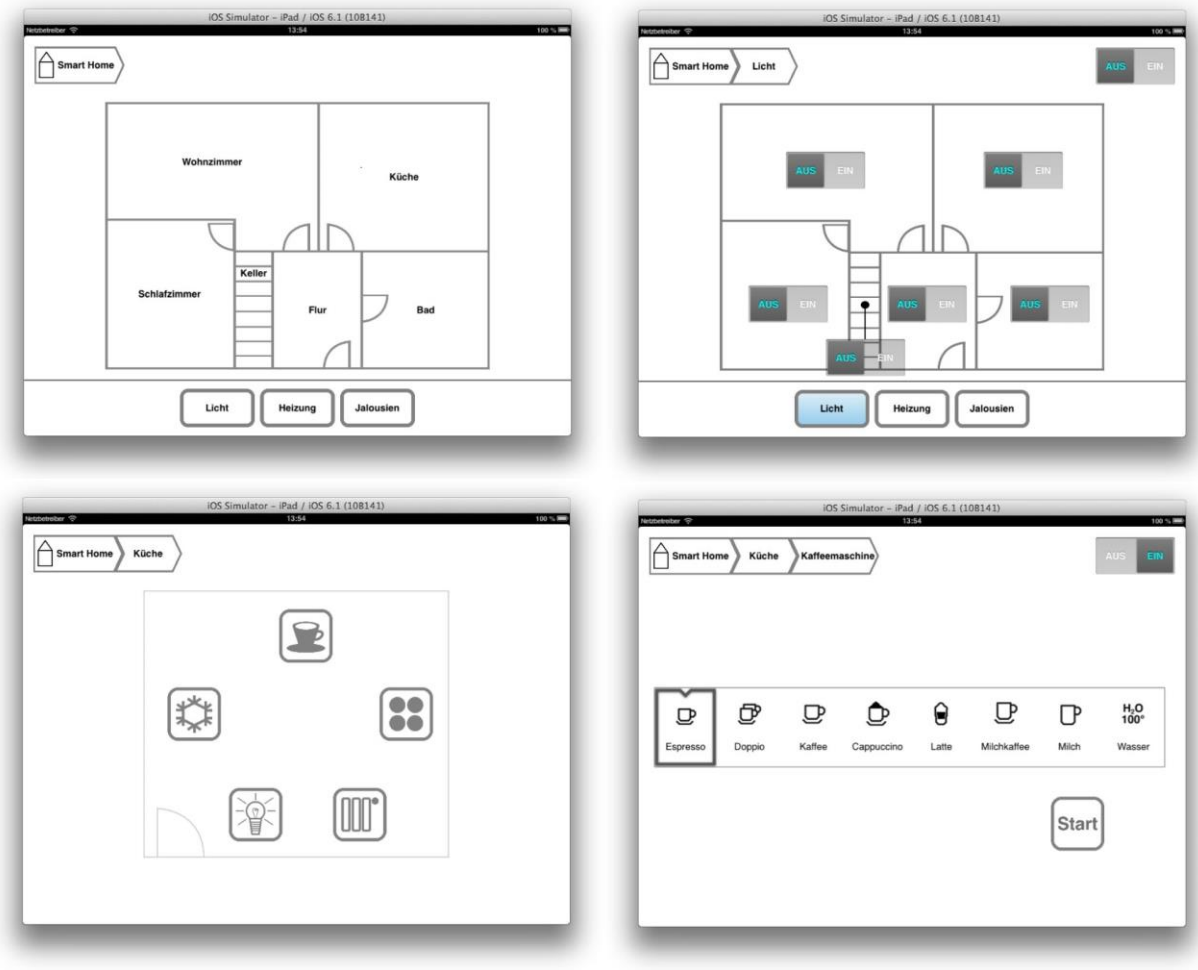

Figure 43: A demonstrator app for smart home control, which was based on the findings of the other studies described in this thesis.

7.8 List Scrolling

A common form of interaction found relevant for many critical task environments is list scrolling (see 6.3). To analyze the effects of direct manipulation and virtual physics on efficiency and error rate during list scrolling, a usability study of seven different interaction concepts was done. Part of this study has been published before by

Breuninger, Popova-Dlugosch, and Bengler (2013). The experiment was conducted by Jakob Haug (Haug, 2012). Each of the chosen variants has been in use in known critical task environments or deemed appropriate for actual use.

The primary goal of the experiment was to test hypotheses 1a, 1b, and 1c (6.4) for the use case of list scrolling. For this use case, the secondary hypotheses 2a, 2c, 3a, and 3a were also of interest. The primary independent variable in this experiment was the difference between the interaction concepts. They differed in their need to be operated with touch gestures to test hypotheses 1, in their use of virtual physics (virtual inertia and drag) to test hypotheses 2, and in their presentation of the content, either paged or continuous, to test hypotheses 3. The properties of the individual variants are described in 7.8.1. The performance of the variants was expected to vary depending on the amount of content that could be scrolled. The second independent variable in the experiment design was the length of the lists that had to be scrolled. Every variant was used with short, medium, and long lists.

The dependent variable to test hypotheses 1a, 2a, and 3a was the total task time, the time it took a participant to select the target items on the lists with a given variant. To measure the error rate in order to test hypothesis 1b, 2c, and 3b, two metrics were observed: overshoots is the number of times a user scrolls the list farther than necessary, so the target item leaves the viewport. This error will not necessarily lead to false selections, but decreases efficiency. It is therefore a correctable error (see 3.1.2.4). The second metric is the number of task errors a user makes. In this experiment, a task error is the selection of a different item than the target item. Since a selection task ended with the tap on a list item, this was an uncorrectable error in this task design. It resulted in an unsuccessful completion of the task. This mirrors realistic tasks in critical task environments, where wrong selections can lead to uncorrectable activation of machinery or processes that might have adverse effects on human safety or economic viability.

To test hypothesis 1c, the usability and user experience of each variant were rated by the participants. The usability questionnaire that was used (see appendix B) consists of a subset of nine questions from the Post Study System Usability Questionnaire or PSSUQ (Lewis, 1992, 1993, 2002) and three questions from the System Usability Scale or SUS (Brooke, 1996). Questions 1–8 (“system usefulness”) and 19 (“Overall, I am satisfied with the system.”) of the PSSUQ and questions 7 & 8 of the SUS, as well as a question concerning error-proneness, were chosen because they are relevant for touchscreen systems, applicable in the experiment, and relevant to critical task environments. The seven-point Likert scale of the PSSUQ was used: “I strongly agree” to “I strongly disagree”. Moreover, the AttrakDiff 2 (Hassenzahl, Burmester, & Koller, 2003) was used to assess the perceived user experience of the variants.

Participants were questioned about their age, sex, frequency of use of touchscreen devices, and technical affinity (see appendix B). This was done to assess the representativeness of the sample, to gain a better understanding how the results might be interpreted and as a mean to control for possible other influence factors besides the interaction concepts. The participants’ technical affinity was rated using the TA-EG questionnaire by Karrer, Glaser, Clemens, and Bruder (2009).

An a priori analysis with G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) calculated a needed sample of 21 people for a repeated measure within-subjects ANOVA with seven measurements of seven groups to detect a large effect ($f = .4$; probability of α error = .05; power = .95; number of groups = 7; number of measurements = 7; correlation among measures = 0; nonsphericitiy correction $\varepsilon = 1$). The presumption of a large effect was based on preliminary tests and experience with comparable research at the Chair of Ergonomics. Since the goal of the research project was to give general recommendations for touchscreen interaction design, a focus on large effects seemed also necessary to strengthen the relevance of the recommendations and the resilience against other influencing factors in systems design (e.g. costs, technology). Nevertheless, study design targeted a larger sample size to have enough power for smaller effects and possible violation of sphericity (Bortz & Döring, 2006; Reinhart, 2015).

The experiment was designed to be conducted with random participants, representative of the working population, but without knowledge or work experience in critical task environments. The tasks were designed to be representative of tasks that occur in critical task environments without needing extensive training of the participants to gain the necessary understanding and reach realistic input speed. This was decided to limit the complexity of the experiment design and ensure a reasonable transferability of the gained insights to different use cases.

7.8.1 Variants

7.8.1.1 Scrollbar

The Scrollbar is one of the oldest and most widespread inter-action concepts for scrolling through lists in software systems with both graphical and textual user interfaces. It is usually located on the right side of the list and often used in machine control systems, especially if they are based on Microsoft Windows. For use on a touchscreen, the position indicator has to be large enough to be dragged with the finger. On most PC operating systems, a scrollbar also allows page-wise scrolling by clicking on the scrollbar above and below the position indicator. Furthermore, there are usually arrow buttons to progress one item/line. While the page-wise scrolling functionality is also practical on touchscreens, the arrow buttons are usually omitted, especially on small screens, because they would have to be considerably larger than on mouse-driven systems, offering very little additional value. The interface implemented for the usability study (see Figure 44 left) supported dragging the position indicator and the possibility to jump immediately to any position by tapping the scrollbar above or below the position indicator. This behavior is more common for touchscreen devices than page-wise scrolling. In contrast to scrollbars on desktop computers, the size of the position indicator was constant. This always ensures sufficient touch size for dragging, but gives no clue how long the list is. When the position is changed by dragging or tapping, a popover index in the upper half of the screen showed the first letter of the topmost item on screen. This feature can be found on devices with Google Android and it facilitates orientation in the list. An item is selected by tapping it. No additional direct manipulation of the items or the list was possible. The scrollbar was expected to allow very fast navigation in long lists because any position can be reached with only one tap. On the other hand, reaching a dedicated item becomes more difficult for longer lists because small movements of the position indicator lead to fast movement of the list itself. As a well-established interface concept, the scrollbar was expected to be quickly recognized and its functionality understood.

7.8.1.2 Page-wise Scrolling with Arrow Buttons

Scrolling with arrow buttons is often found in key-driven software systems. On those systems, the keys mostly progress a selection indicator by one item/line. For long lists, they often offer additional (e.g. double-arrow-labeled) keys to progress the selection indicator by a larger step like ten items or page-wise. For touchscreens, there is normally no selection indicator, as it is an integrated pointing device making this additional action unnecessary. It is only required to move the list in such a way that the desired item appears somewhere on screen and then can be selected by tapping. That is why for the usability study a variant was implemented that scrolls the list page-wise when tapping arrow buttons on the right side of the list (see Figure 44 right). Scrolling with arrow buttons was expected to be intuitively understood by participants and to yield fast and error free navigation for short and medium lists. On longer lists, speed is limited because several taps are needed and it is possible to overshoot the correct page with the desired item. The button-based interaction without direct manipulation might be considered old-fashioned by participants used to modern touchscreen devices. Featuring paged content, the scroll task can be easily interrupted and continued, which is advantageous in use cases with a parallel monitoring task (Kujala & Saariluoma, 2011).

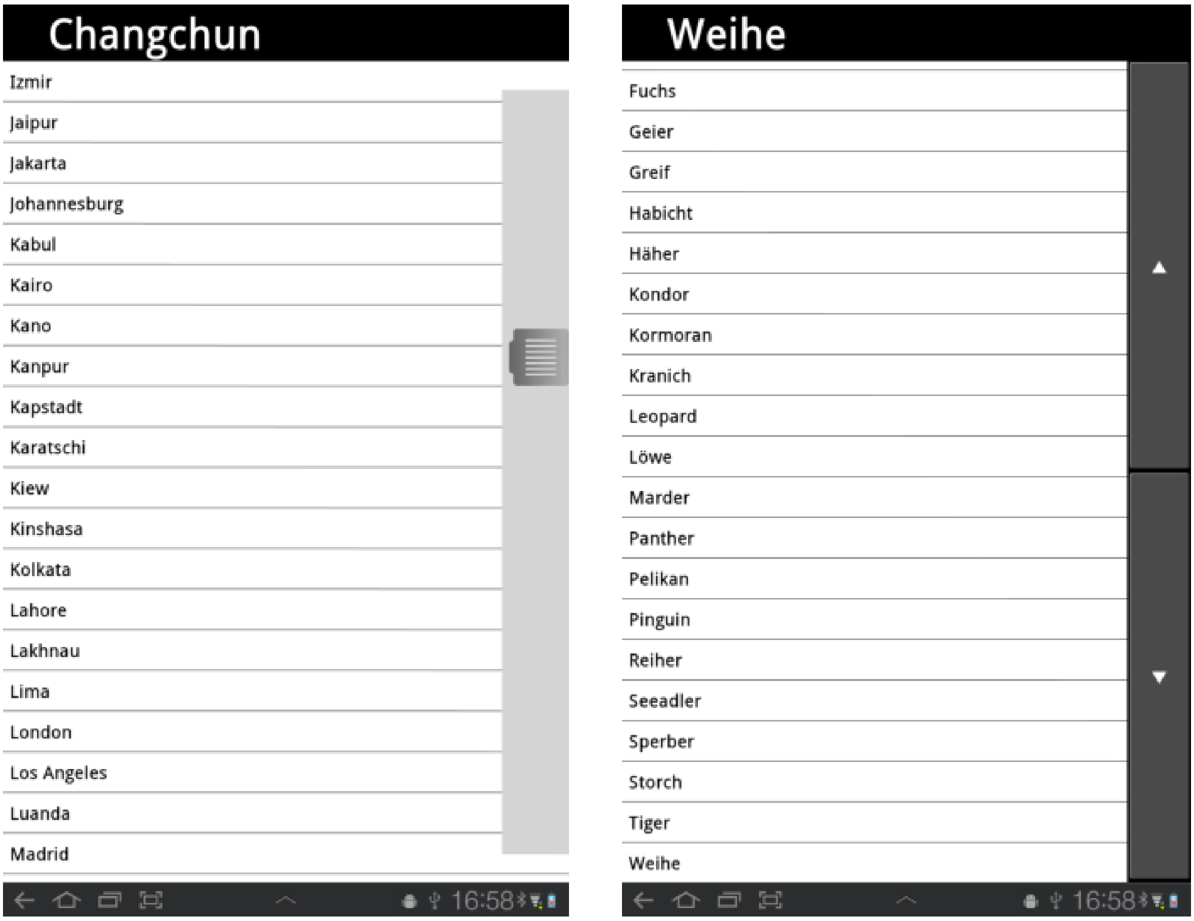

Figure 44: The Scrollbar (left) and the Arrow Buttons (right)

7.8.1.3 Page-wise Scrolling with Direct Manipulation

A modern variant of the arrow buttons is page-wise scrolling by direct manipulation. In this variant, there are no buttons, but the list can be progressed page-wise with a sliding gesture. This touch gesture is commonly found in tablets and e-book readers that mimic the interaction of turning a page in a book. When turning a page in a book the gesture is carried out horizontally. For scrolling in lists, which are thought to continue above and below the visible part on screen, the gesture is carried out vertically. An animation suggests that the continuous list moves exactly the number of items that fit on screen. This variant was expected to offer the same advantages and disadvantages as the arrow buttons and to be considered more natural, modern, and fun to use. An additional disadvantage of omitting the buttons is that there is little visual clue for the user how the interaction with the lists works (see Figure 45 left). Users might not even recognize the possibility of scrolling at all (Huang & Wang, 2011). If this is the case, the list is lacking feedforward (see 4.4.1 and Norman, 1988). Another disadvantage of all direct manipulation variants is the danger of false selections of items when swiping gestures are carried out in a small area, too quickly or too imprecisely.

7.8.1.4 Direct Manipulation of a Continuous List with Virtual Physics

The most common way of scrolling through lists on modern consumer touchscreen devices is direct manipulation of the list, which can be made to move continually for a certain time. The variant implemented in the usability study (see Figure 45 left) showed the standard behavior of lists on devices with Android. The list could be scrolled by dragging items; it could be set in motion by releasing the finger while still in motion during a swiping gesture. A tap selected the desired item. This way of interaction is considered natural and easy to learn and is the standard in consumer electronics. It allows fast navigation of short and medium lists and the continuing motion allows scrolling through long lists with fewer interactions than variants with paged content. On the other hand, the motion has to be actively stopped by the user when approaching the desired item on the list. This requires accurate monitoring and quick reaction and it might be a source of false selections. Additionally, the possibility to overshoot the target is immanent, especially in large lists. Since the user grabs the list items themselves, there are no visible interaction elements; this concept again lacks feedforward. Since this variant is widely established, it was expected that users with touchscreen experience would interact intuitively with the list in this way.

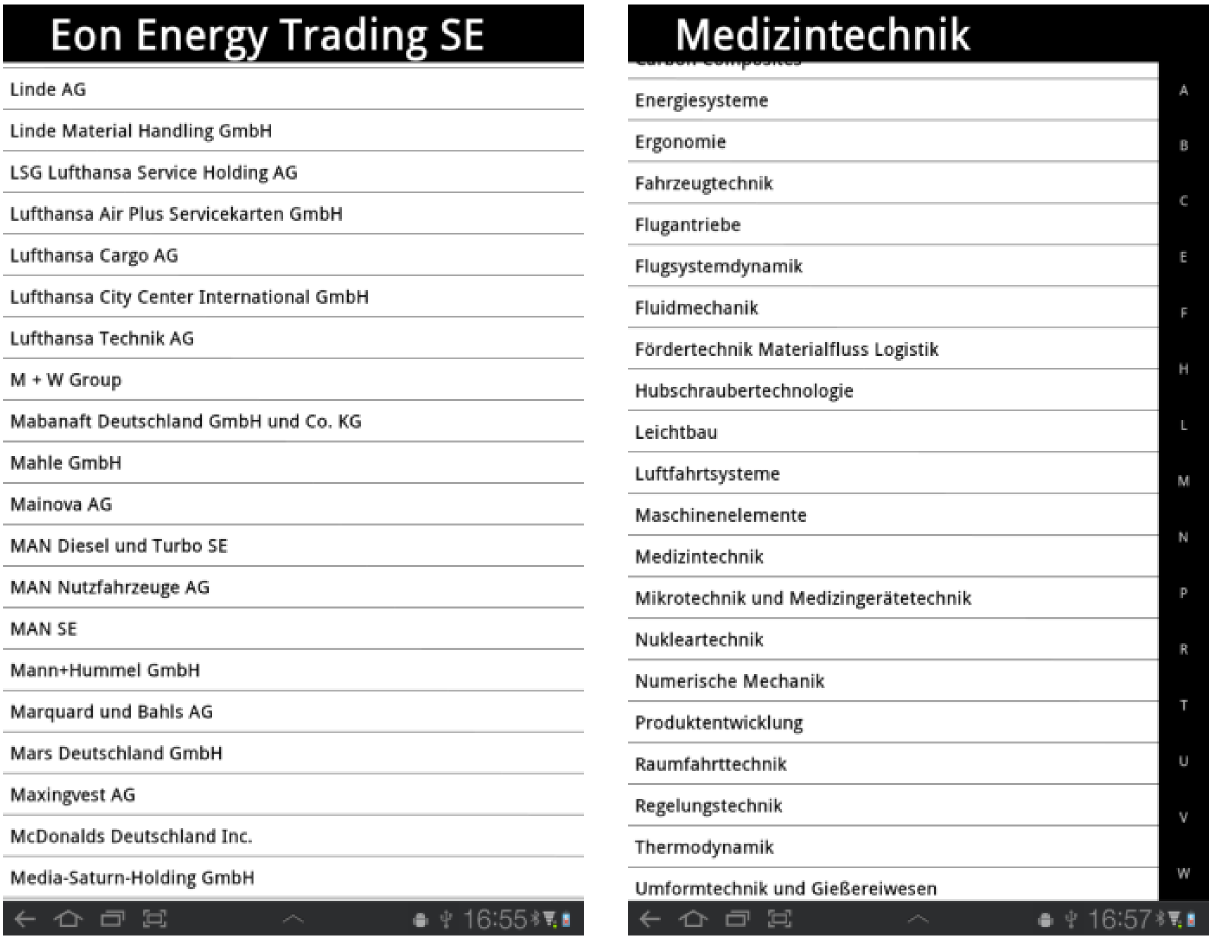

Figure 45: Direct Manipulation (DM, left) and DM with Alphabetic Index Bar (right)

7.8.1.5 Direct Manipulation of a Continuous List without Virtual Physics

The possibility of overshooting the target item once or even several times in a row does not seem appropriate in use cases with a high demand for error-free, safe, and efficient operation. Therefore, a variant was implemented (see Figure 45 left) that allows direct manipulation of the list, but does not allow setting the list in continuing motion. When the user’s finger leaves the touchscreen, the list immediately stops at its current position. This leads to considerably more interaction steps when navigating through long lists, but was expected to lead to fewer errors and more efficiency on short and medium lists. The problem of lacking feedforward remains. While this kind of interaction with lists is not state of the art anymore, it can still be found in older, mostly stationary touchscreen systems. Users were expected to understand the behavior of this variant quickly.

7.8.1.6 Direct Manipulation of a Continuous List with Virtual Physics and an Alphabetic Index Bar

The shortcomings of continuous lists with direct manipulation are usually addressed by combining the possibility of direct manipulation with an additional interaction element, like a scrollbar or an alphabetic index bar; the former is the standard behavior of Android devices, the latter is used in Apple's iOS. It allows fast jumps in the approximate region of the desired list item and direct manipulation as a natural way to navigate quickly to the item itself. To observe how often users would use this function, another variant of the continuous list with physics was implemented. It features an alphabetic index bar on the right side of the list (see Figure 45 right). By tapping on a letter on the bar, the list will instantly jump so that the first item beginning with this letter will be on top. It is also possible to keep the finger on the index bar and move it over the letters to scroll the list, like with a scrollbar. Unlike the position indicator of the scrollbar though, there is no interaction element that can be grabbed or that indicates the current position. Nevertheless, the feedforward of the user interface is somewhat improved over the former three variants by the additional interaction element, the index bar. However, since it gives little visual clue in what way it can be manipulated, users might have varying expectations. Nevertheless, it was expected that participants understood the functionality quickly after trying it out. The main disadvantage of the alphabetic index bar is the fact that precise navigation to a desired letter is only possible on large screens. On smaller screens, single letters are too small for exact selection with the fingertip when the whole alphabet (possibly with additional symbols) is arranged in a line. Even worse, in this case the finger obstructs the view of the targeted letter and those adjacent. To give users better feedback at which position the device detected the users' finger, the selected letter was shown above it when touching the alphabetic index bar. Moreover, only letters that were initials of actual list items were displayed on the index bar. To scroll down on the list the finger has to move downwards on the index bar, but upwards when manipulating the list itself. The index bar/scrollbar is meant as a mean of moving the view over a "stationary" list. Manipulating the list directly suggests that the list moves along a stationary area of view. The fact that manipulating the list and manipulating the index bar follow opposite mappings could be a source of error (Norman, 1988). As mentioned above, in spite of these possible disadvantages, direct manipulation with an additional index bar is the most widespread interaction method for large alphabetic lists. It was expected to be recognized by most users with touchscreen experience and to be used efficiently on lists of all lengths.

7.8.1.7 Direct Manipulation of a Continuous List without Virtual Physics and with an Alphabetic Index Bar

The last variant is again a modification of the continuous list that can be manipulated directly. It does not allow the user to set the list into continuous motion but stops immediately after the finger leaves the touchscreen. It features the alphabetic index bar described above (see Figure 45 right). It was intended to allow fast operation on long lists avoiding the large number of touch gestures needed without the index bar. Since overshooting an item is less likely, it was expected to be less error-prone than the variants with physics and just as easily understood by users.

7.8.2 Procedure

The usability study for list scrolling was conducted in a usability lab at the Chair of Ergonomics of Technische Universität München (see Figure 46). Participants were instructed to perform different selection tasks on several lists on a Samsung Galaxy Tab tablet with an 8.9" screen and Android 3.2. The tablet was held in portrait mode. The participants had to operate the tablet while standing. This was in order to simulate the posture and physical load of mobile touchscreen interaction in an industrial environment. While carrying out the tasks, the interaction with the touchscreen was recorded on video from above. After all tasks with a variant were completed, the participant sat down and completed a questionnaire on a PC. An experimenter instructed the participants and was present in the same room, though separated from the participants by a screen during the task completion. Each participant had to get to know each list scrolling variant and use it to fulfill several item selection tasks.

Figure 47 shows a flow chart of the procedure for a single participant. After being presented a variant, the participant was instructed to try it out until he or she felt comfortable using it and had understood all its features. After this trial phase, the participant had to rate the following statements: “I understood how this user interface works by looking at it” and “I understood how this user interface works after trying it out”, on a five point Likert scale, from “I strongly disagree” to “I strongly agree”. If a method of interaction remained undiscovered by the participant, this was documented. The ex-

perimenter explained the full functionality of the interaction concept and the participant was again given time to try it out.
Participants were instructed to solve the presented tasks promptly, but with precision, as if it was their daily job. No time budget was defined or enforced to simulate a work environment with some, but no immediate time pressure. This design was chosen to limit the dependency of the results on a specific task design (compare 3.1.1.2) and omit inducing unrealistically high error rates. Due to general task design and the varying experience of the participants, introducing an arbitrary time budget would probably have led to further variance of the results with more uncertainty in interpretation. It would also have required longer training for participants to ensure realistic and effective task solving. Since all uses of list scrolling that had been observed at industrial environments did not rely on being performed within a defined time frame (Breuninger et al., 2012), this simpler experiment design seemed justified.

Figure 46: A participant in the usability lab

After pressing a start button, an item was shown at the very top of the screen. The participant had to select this item in the list, which filled the rest of the screen (except the android system bar at the bottom). When selecting an item, correctly or incorrectly, visual and acoustic feedback was given and the list changed to a different one and a new item had to be selected. Each selection task started at the top of the list. There were 15 different lists of three different lengths. The five short lists contained 1.5 to 2 times the number of items that fit on the screen. The five medium lists contained about five screens and the five long lists about 20 screens. The content of the short lists was animals, cities, colors, university institutes, university professors; medium lists: chemical elements, movie characters, movie titles, herbs, international cities; long lists: celebrities, companies, rivers, streets, towns. The participants had to conduct ten selection tasks with each list length, so each list appeared twice. After those ten tasks with the same list length, participants had to rate if this interaction variant was suitable for this list length with the above-mentioned Likert scale.

After completing all three list lengths with the same variant, participants answered questionnaires concerning usability and user experience of the variant. The procedure was repeated six times to examine all seven variants. Both the order of the variants and the order of the list length were permuted across participants to compensate for an expected learning effect. While no list item had to be selected twice by the same participant, each participant had to select items from the same regions of the lists with each variant. In the end, participants could choose up to three variants that they liked and disliked for daily work with all three list lengths.

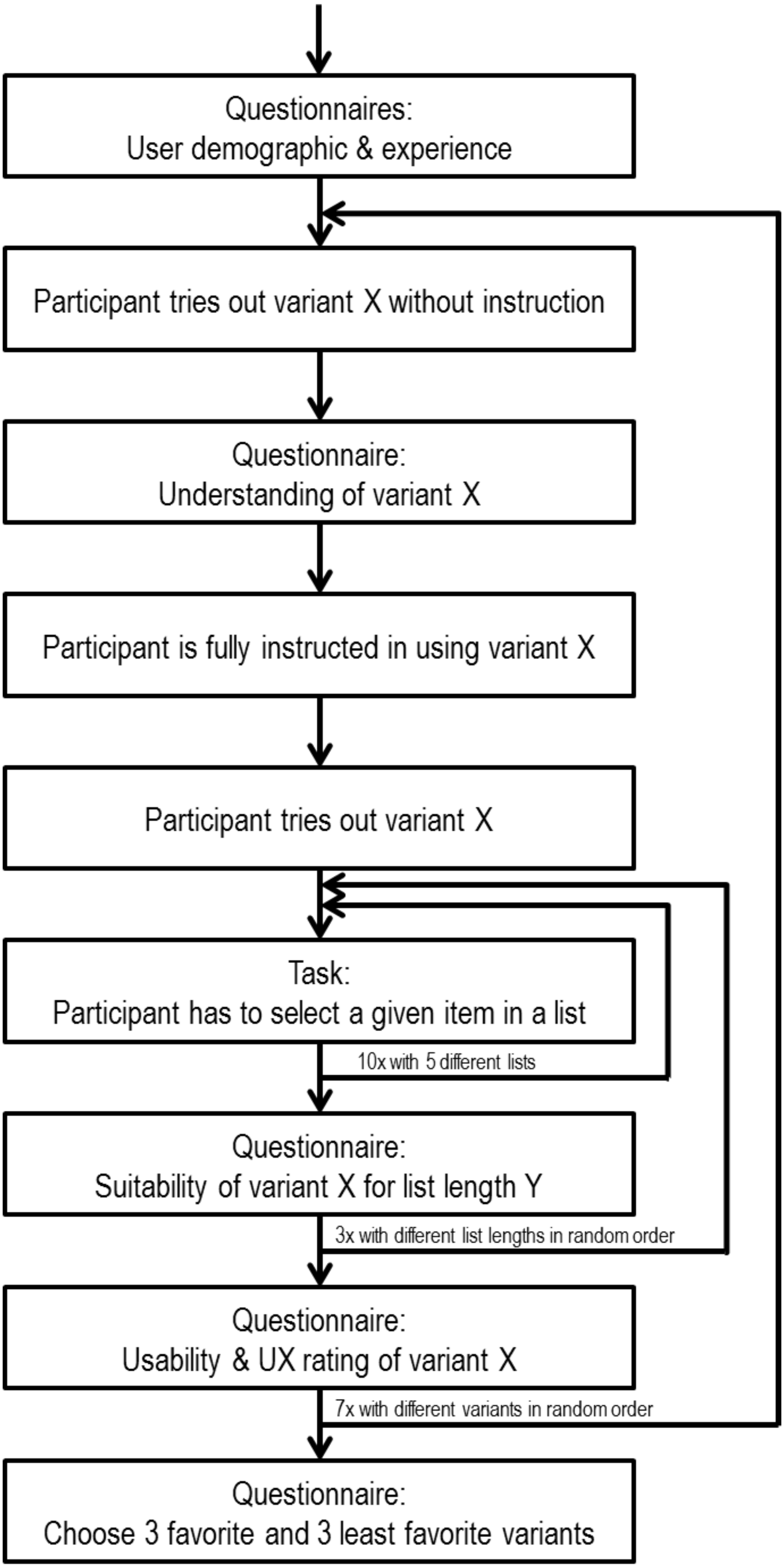

Figure 47: A flow chart of the steps a participant had to go through in the experiment for list scrolling

7.8.3 Results

Thirty-two people voluntarily participated in the study (25 male, 7 female; age 20–62, M = 32.3, SD = 13.71). Almost all participants had some experience with touchscreen devices. Many regularly used smartphones and sometimes navigation systems (see Figure 48). Participants scored an average of 2.83 on the TA-EG questionnaire for technical affinity (SD = .44).

The women in the sample were slightly younger than the men ($r = .28$, $p = .11$). On average, older participants had less overall touchscreen experience ($r = -.29$, $p = .11$). There was a significant correlation between age and smartphone use ($r = -.51$, $p < .005$). The technical affinity of the participants also correlated slightly with their age ($r = -.33$, $p = .07$). The participants' sex did not correlate with their smartphone use ($r < .01$, $p = .97$). However, on average, women had a slightly lower experience with touchscreen devices ($r = -.26$, $p = .14$) and technical affinity ($r = -.21$, $p = .25$). There was a significant medium correlation between participants' overall touchscreen experience and their technical affinity ($r = .41$, $p < .05$). The correlation was even a little stronger for smartphone use and technical affinity ($r = .50$, $p < .005$).

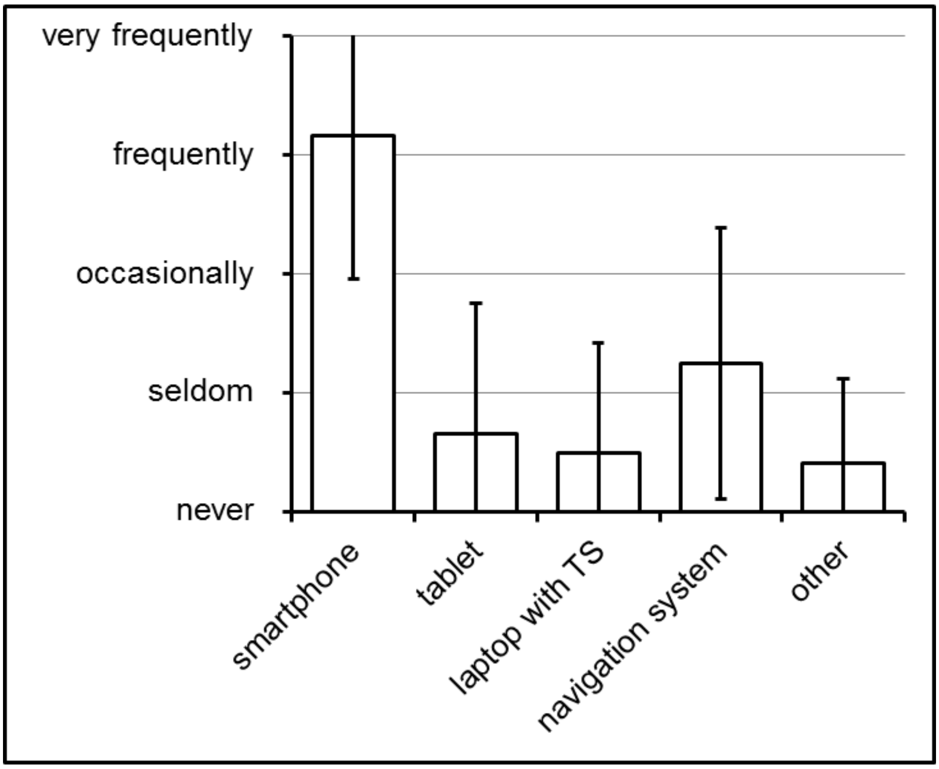

Figure 48: Average participant experience with touchscreen devices. Error bars show ± 1 standard deviation.

When judging the feedforward of the variants (7.8.2), participants stated that they understood all variants after looking at them ($M > 2.9$; on a scale 0–4) except page-wise direct manipulation ($M = 1.7$). The variance of the results (between .8 and 1.5 SD) and the difference between equal-looking variants indicate that participants were unable to describe their perception objectively. Therefore, the results are inconclusive. Participants fully agreed with the second statement about the ease of learning ($M > 3.8$) for all variants except page-wise manipulation ($M = 3.1$). Four participants did not realize that with this variant scrolling moved the list exactly one page of 20 items. Trying the variants with the alphabetic index bar, six participants (with physics) respectively eleven participants (without physics) did not discover the whole functionality. These participants mainly missed the possibility to slide on the index bar in addition to tapping. The possibility of setting the list into motion was overlooked twice. For the variant without physics, the possibility of direct manipulation of the list was not discovered by six participants. This again shows that the self-assessment by study participants is an inadequate mean for judging feedforward and learnability.

7.8.3.1 Total Task Time

There were considerable differences in total task time between the interaction variants. A two-way repeated-measures ANOVA was used to determine if significant difference in total task time between variants occurred (Field, 2009). The seven variants were the first independent variable and the list length was the second independent variable.

Mauchly's test revealed that the assumption of sphericity in the data had been violated for the effect of the list length ($\chi^2(2) = 41.45$, $p < .001$) and the interaction between the concept and the list length ($\chi^2(77) = 188.93$, $p < .001$). Therefore, degrees of freedom were reduced using Greenhouse–Geisser estimates of sphericity ($\varepsilon = .57$ for list length and $\varepsilon = .40$ for interaction between the concept and list length).

All main effects are reported significant at $p < .001$. There was a significant effect of the kind of interaction concept on total task time ($F_{4.33, 134.25} = 91.24$). A Holm-Bonferroni post-hoc test showed that page-wise direct manipulation was slower than all other variants (Figure 49). Second slowest was direct manipulation without physics, followed by the indistinguishable group of buttons, scrollbar and direct manipulation with physics. Direct manipulation with and without physics and an alphabetic index bar resulted in the shortest total task time.

As expected, there was also a significant effect of list length on total task time ($F_{1.14, 35.45} = 750.85$). A Holm-Bonferroni post-hoc test shows significant differences between all three list lengths. The differences in total task time occurred mostly on long lists. When scrolling and selecting items in short lists, the differences between the interaction variants were very small: With all variants, it took the participants between four and five seconds for one selection task with a standard deviation of about one second.

There was also a significant interaction effect between the concepts and list lengths ($F_{4.74, 147.04} = 77.61$). While the scrollbar and especially concepts with an alphabetic index bar showed a great advantage in total task time on long lists, they were slower than other concepts on short lists (Figure 50).

Details on the statistical analysis of total task time can be found in appendix A.

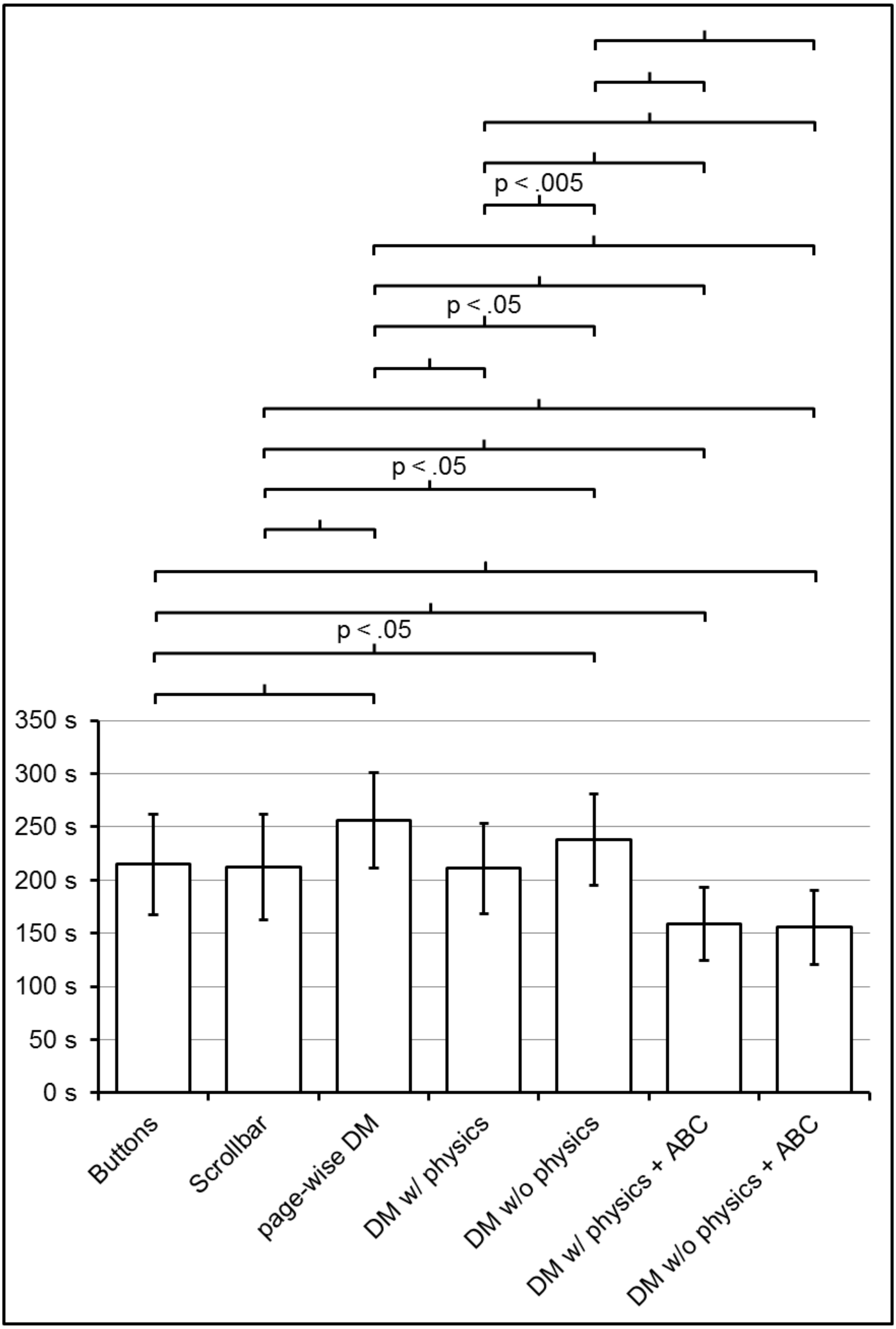

Figure 49: Total time for task completion. Variants connected by brackets are significantly different ($p < .001$, unless the significance level is stated explicitly). Error bars show ± 1 standard deviation.

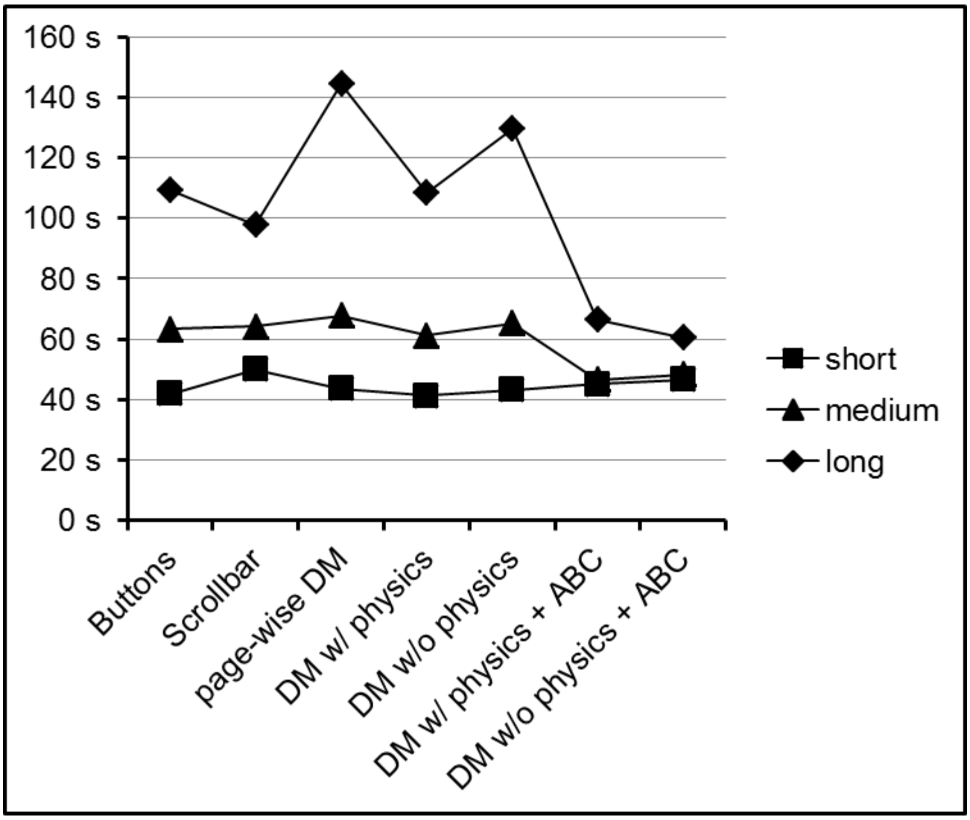

Figure 50: Total task time for different list lengths. Differences occur largely on long lists. Scrollbar and alphabetic index bars show advantages for long lists, but disadvantages for short lists compared with other variants.

7.8.3.2 Overshooting

Analogous to total task time, a two-way repeated-measures ANOVA was used to determine if significant difference in overshoots between variants occurred. Mauchly's test revealed that the assumption of sphericity in the data had been violated for the interaction between the concept and the list length ($\chi^2(77) = 108.82$, $p < .05$). Therefore, degrees of freedom were reduced using Greenhouse–Geisser estimates of sphericity ($\varepsilon = .63$).

All main effects are reported significant at $p < .001$. There was a significant effect of the kind of interaction concept on overshooting ($F_{6,186} = 46.42$). A Holm-Bonferroni post-hoc test shows that direct manipulation without physics and direct manipulation with alphabetic index bar led to fewer overshoots than all other variants (Figure 51). Most overshoots occurred with the scrollbar and buttons. The exact order of the variants could not be determined based on the data of this experiment.

List length also has a significant effect on overshooting ($F_{2,62} = 478.99$). A Holm-Bonferroni post-hoc test shows significant differences between all three list lengths. On short lists, the number of overshoots was negligible (Figure 52).

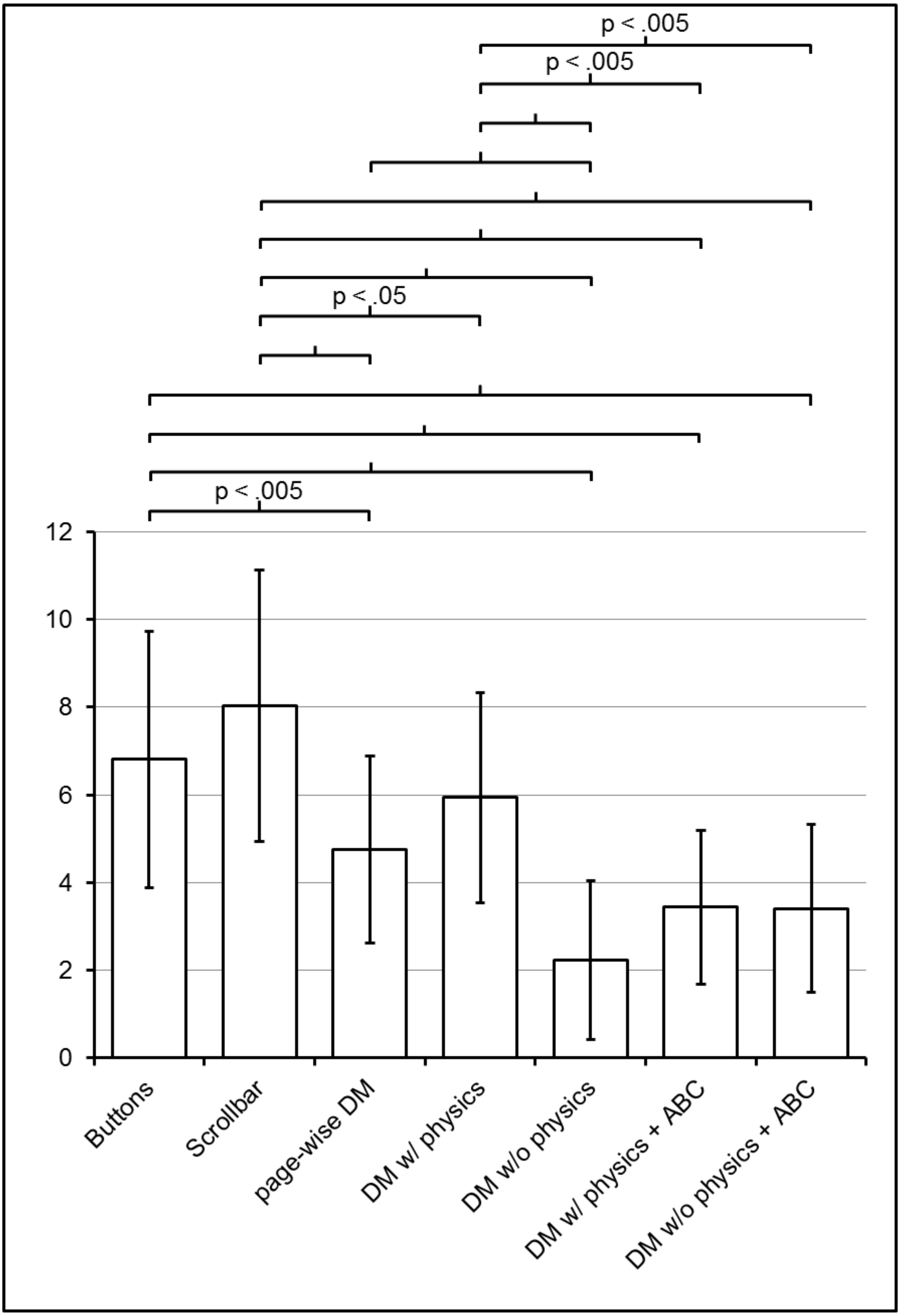

Figure 51: Number of overshoots during completion of 30 tasks. Variants connected by brackets are significantly different ($p < .001$, unless the significance level is stated explicitly). Error bars show ± 1 standard deviation.

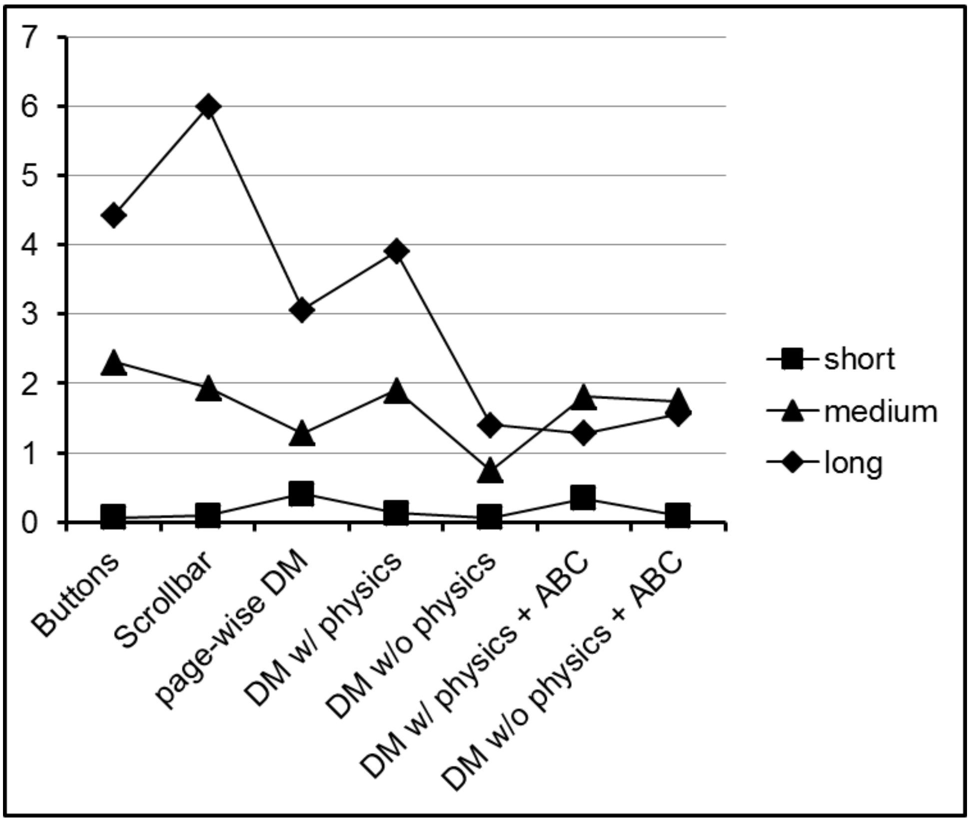

Figure 52: Overshoots for different list lengths. There are almost no overshoots on short lists. Page-wise direct manipulation leads to more overshoots on short list, but to fewer overshoots on medium and long lists compared to some other variants. Direct manipulation with physics and alphabetic index bar had the fewest overshoots on long lists, while it had more on short and medium lists.

There was a significant interaction effect between the concepts and list lengths ($F_{4.74, 147.04} = 77.61$). The scrollbar showed only an average amount of overshooting on medium and short lists, but led to the most overshooting on long lists. Direct manipulation with physics and an alphabetic index bar also had a higher number of overshoots than some others on short and medium lists in contrast to long lists, where it performed better than all other variants (Figure 52).

There was little correlation between total task time and overshoots ($r = .20$, $p = .67$). Details on the statistical analysis of overshoots can be found in appendix A.

7.8.3.3 Error Rate

The selection of any item other than the target item was considered an error. Two kinds of errors were defined. If the falsely selected item was the item directly above or below the target item this was considered a slip (Norman, 1983) due to lacking precision; these were excluded from the calculation of the error rate. The participants had probably located the target item, but failed to tap on the right spot. All other false selections were considered unintentional, and therefore errors that can occur when the wrong interaction method is applied (e.g. tap on the wrong location) or an interaction method is misinterpreted by the device (e.g. a sloppily executed swiping gesture is recognized as a tap).

As expected, the total number of precision slips showed no significant difference between variants ($F_{4.09, 126.67} = 1.18$, $p = .33$; Greenhouse–Geisser corrected $\varepsilon = .68$). However, the number of unintentional selections differed significantly between variants ($F_{2.9, 89.91} = 13.9$, $p < .001$). According to a Holm-Bonferroni post-hoc test, page-wise direct manipulation and direct manipulation without physics had a higher error rate than buttons, scrollbar, and both forms of direct manipulation with alphabetic index bar (Figure 53).

List length also has a significant effect on error rate ($F_{1.4, 43.45} = 22.05$, $p < .001$). A Holm-Bonferroni post-hoc test showed significant differences between all three list lengths. While the error rate was very similar on short and medium lists, ranging between 0% and 2.5% error rate on average for a task, on long lists error rate reached up to 10% for direct manipulation without physics.

There was a significant interaction effect between the concepts and list lengths ($F_{5.09, 157.64} = 5.08$, $p < .001$). This is caused mainly by direct manipulation with physics, which showed an inconsistently high error rate compared to other variants on medium lists, and direct manipulation without physics and an alphabetic index bar, which showed an inconsistently high error rate on long lists (Figure 54).

There was no statistically significant correlation between overshoots and error rate. The observed correlation in the sample was even negative ($r = -.60$, $p = .15$). The correlation between total task time and error rate in the sample was also not statistically significant ($r = .63$, $p = .13$).

Details on the statistical analysis of error rate can be found in appendix A.

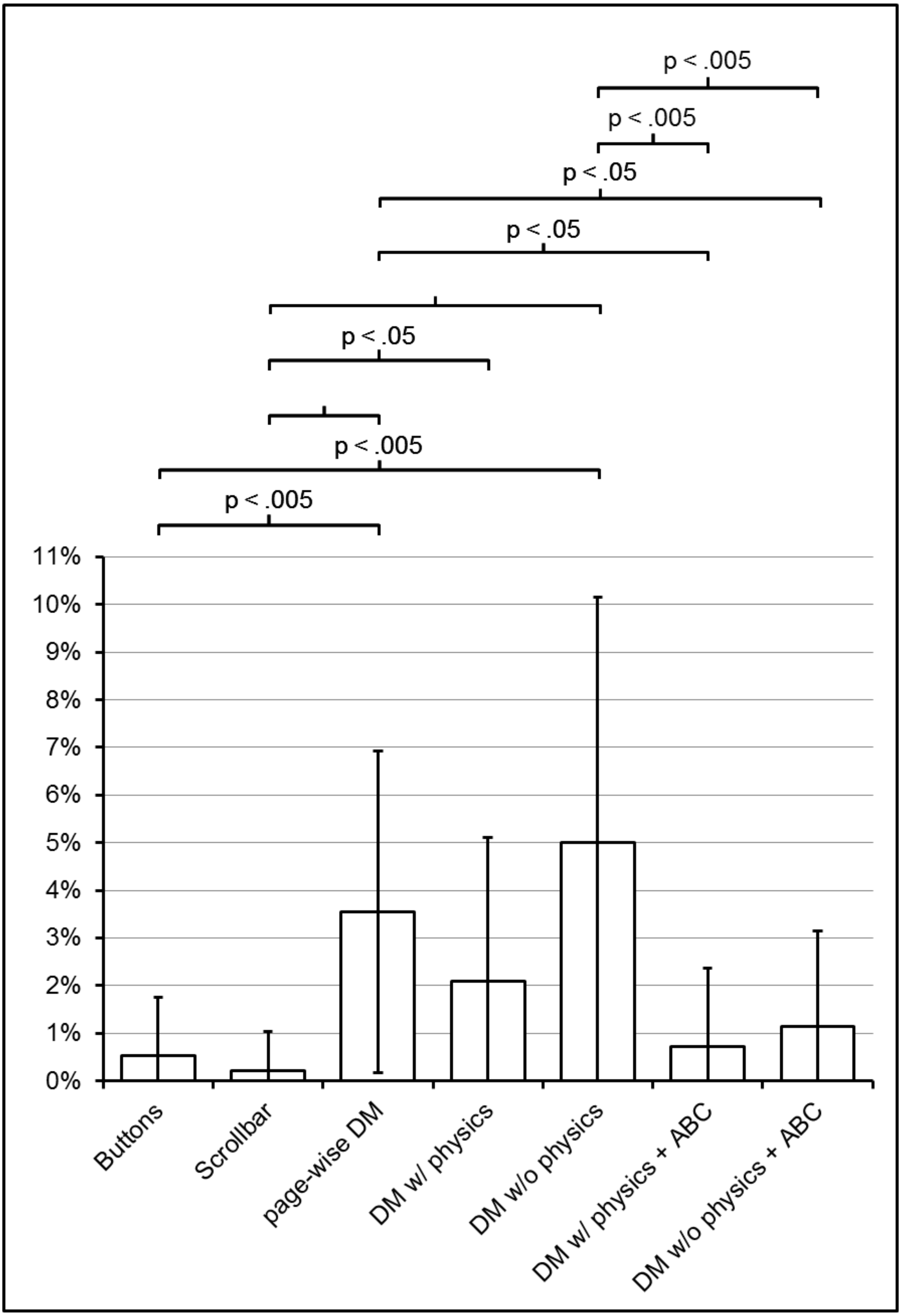

Figure 53: Average error rate during task completion. Variants connected by brackets are significantly different ($p < .001$, unless the significance level is stated explicitly). Error bars show ± 1 standard deviation.

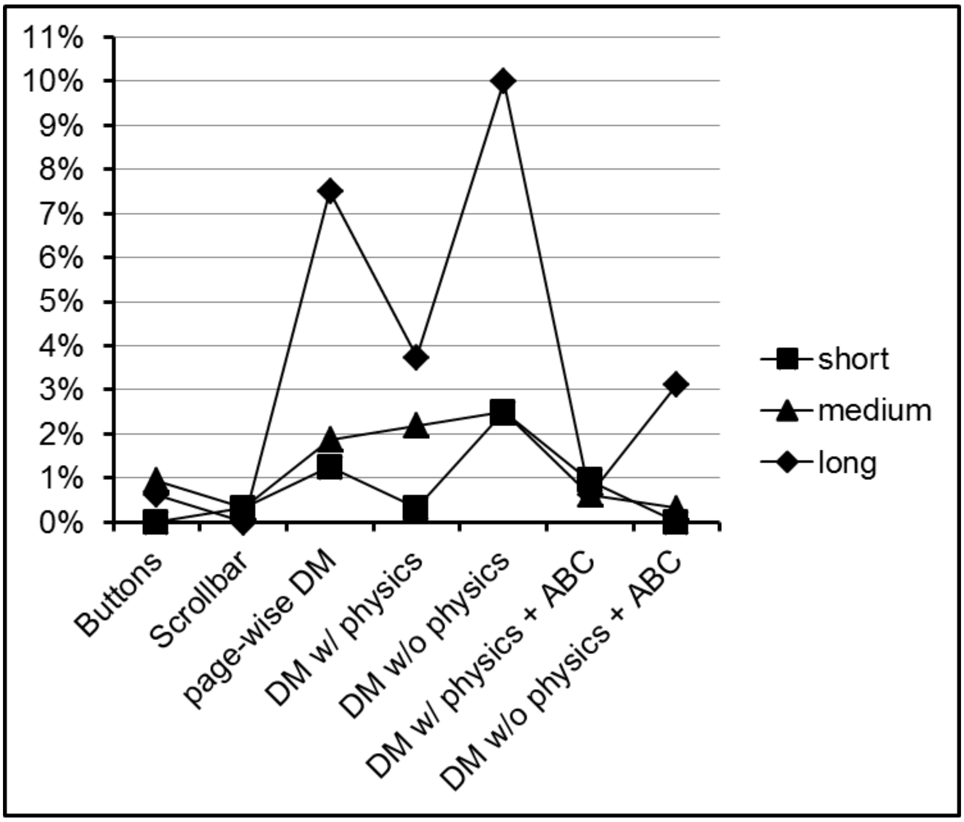

Figure 54: Average error rate during task completion for all three list lengths. Direct manipulation without physics and alphabetic index bar shows an inconsistently high error rate on long lists. Direct manipulation with physics shows an inconsistently high error rate on medium lists.

7.8.3.4 User Rating

A one-way repeated-measures ANOVA was used to show that significant difference between variants occurred in the average score of the usability questionnaire ($F_{6, 186} = 53.85$, $p < .001$). Bonferroni post-hoc tests show that the variants with alphabetic index bar were rated best, while page-wise direct manipulation and direct manipulation without physics were rated worst (Figure 55). Buttons, scrollbar, and direct manipulation with physics lay in between.

For the differences between AttrakDiff scores Mauchly's test was violated ($\chi^2(20) = 54.11$, $p < .001$), so degrees of freedom were adjusted using Greenhouse–Geisser correction ($\varepsilon = .61$). The result shows that the variant significantly affected AttrakDiff score ($F_{3.66, 113.46} = 44.55$, $p < .001$). The order of the variants was identical to the usability questionnaire. The alphabetic index bar variants scored highest, page-wise direct manipulation and direct manipulation without physics scored lowest (Figure 56).

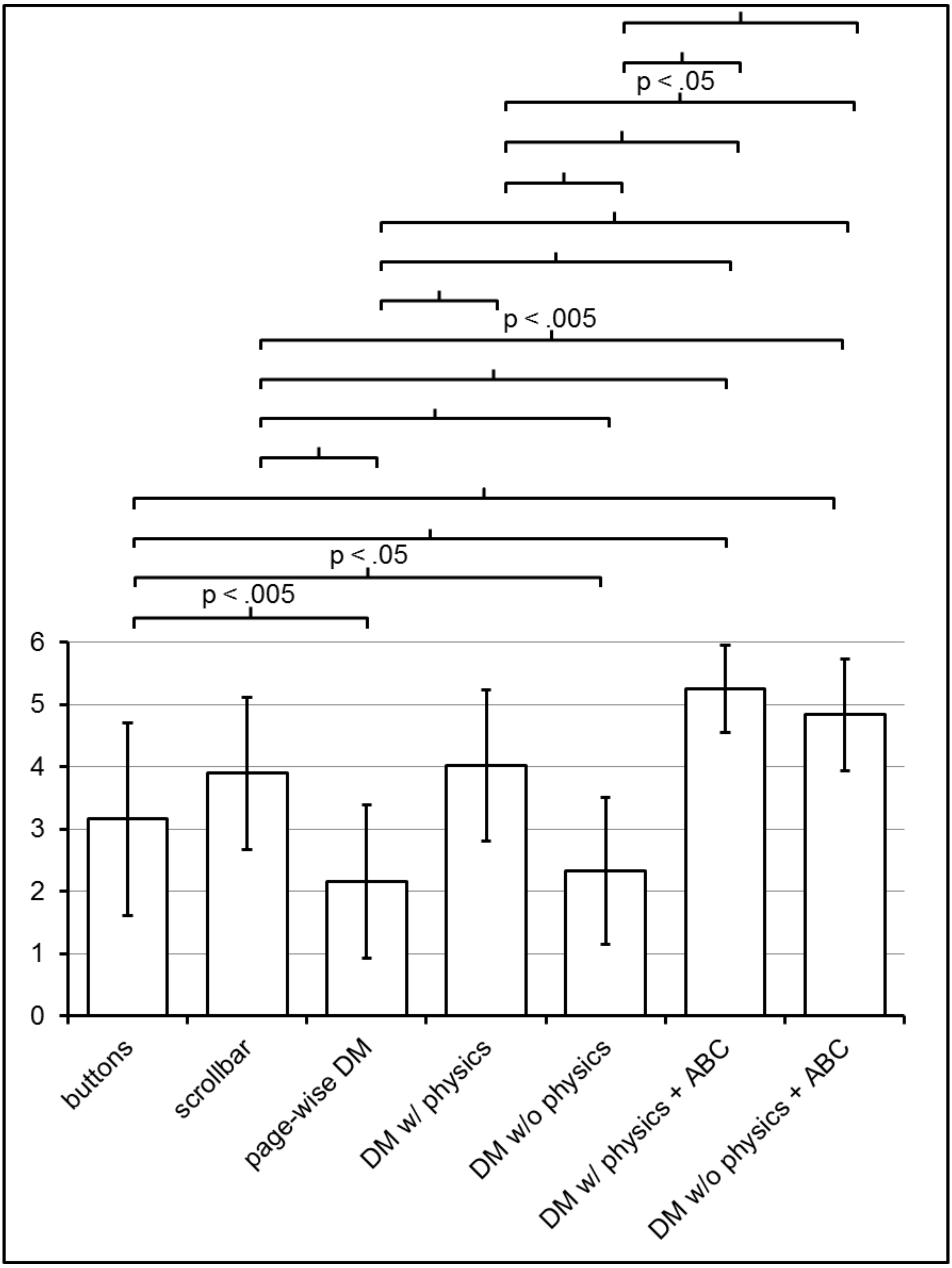

Figure 55: Avg. usability questionnaire score. Scale ranges from "I strongly disagree" (0) to "I strongly agree" (6). Variants connected by brackets are significantly different ($p < .001$, unless the significance level is stated explicitly). Error bars show ± 1 standard deviation.

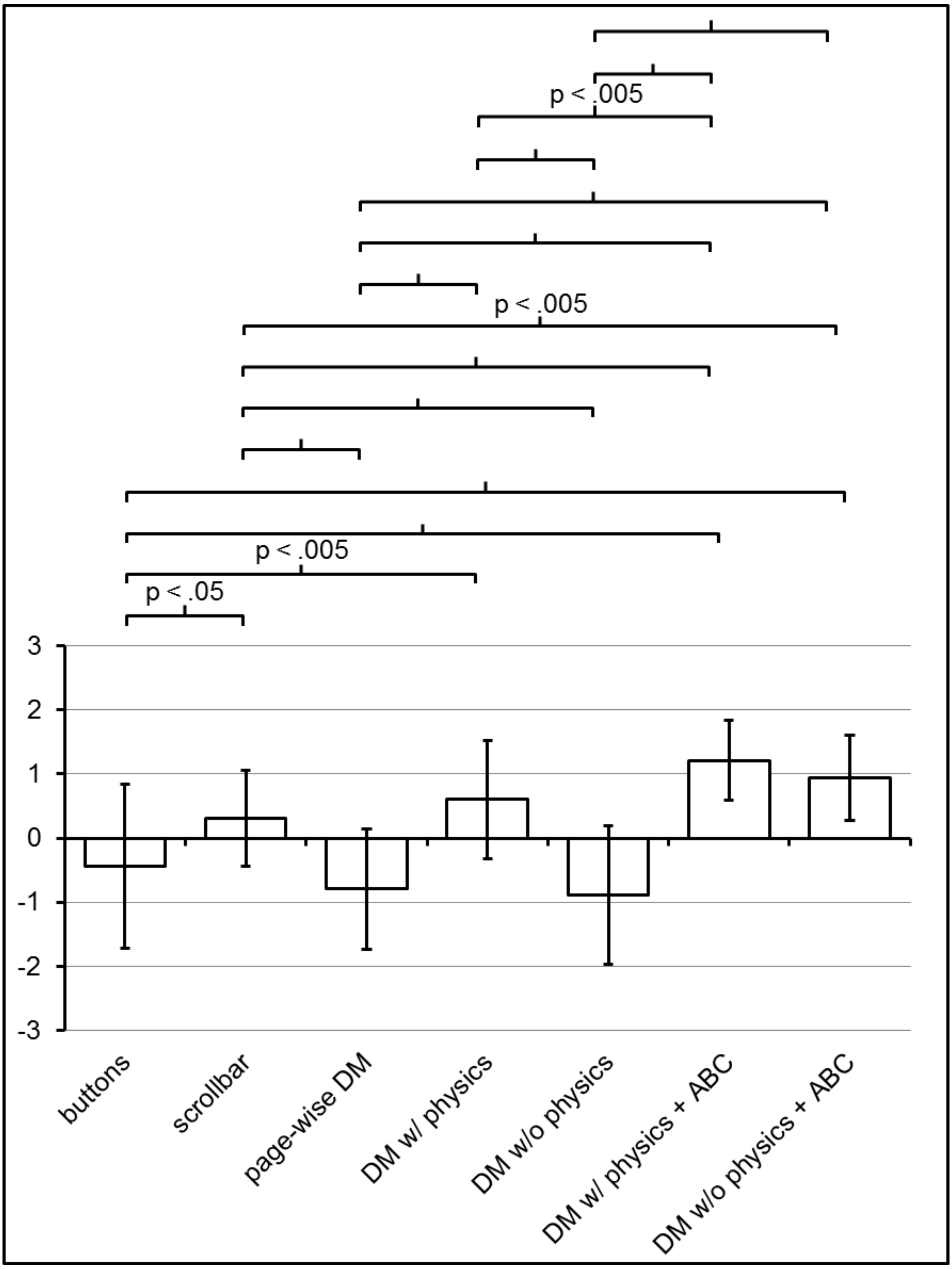

Figure 56: Avg. AttrakDiff scores. Variants connected by brackets are significantly different ($p < .001$, unless the significance level is stated explicitly). Error bars show ± 1 standard deviation.

Both the results of the usability questionnaire and the AttrakDiff questionnaire correlated very strongly with total task time ($r = -.95$, $p < .005$; $r = -.91$, $p < .05$). User rating showed no correlation with overshoots ($r = -.01$, $p = .98$ with usability; $r = .002$,

$p = .997$ with AttrakDiff). A correlation with error rate could not be proven ($r = -.71$, $p = .07$ with usability; $r = -.66$, $p = .11$).

When asked which variant they would prefer for daily use, 30 participants chose direct manipulation with physics and alphabetic index bar (Figure 57). The variant without physics and with index bar was the second most popular, chosen 17 times. Direct manipulation with physics and the scrollbar both received twelve likes. The scrollbar also received nine dislikes, direct manipulation three. Most unpopular were page-wise direct manipulation (25 dislikes), direct manipulation without physics (24 dislikes) and buttons (17 dislikes).

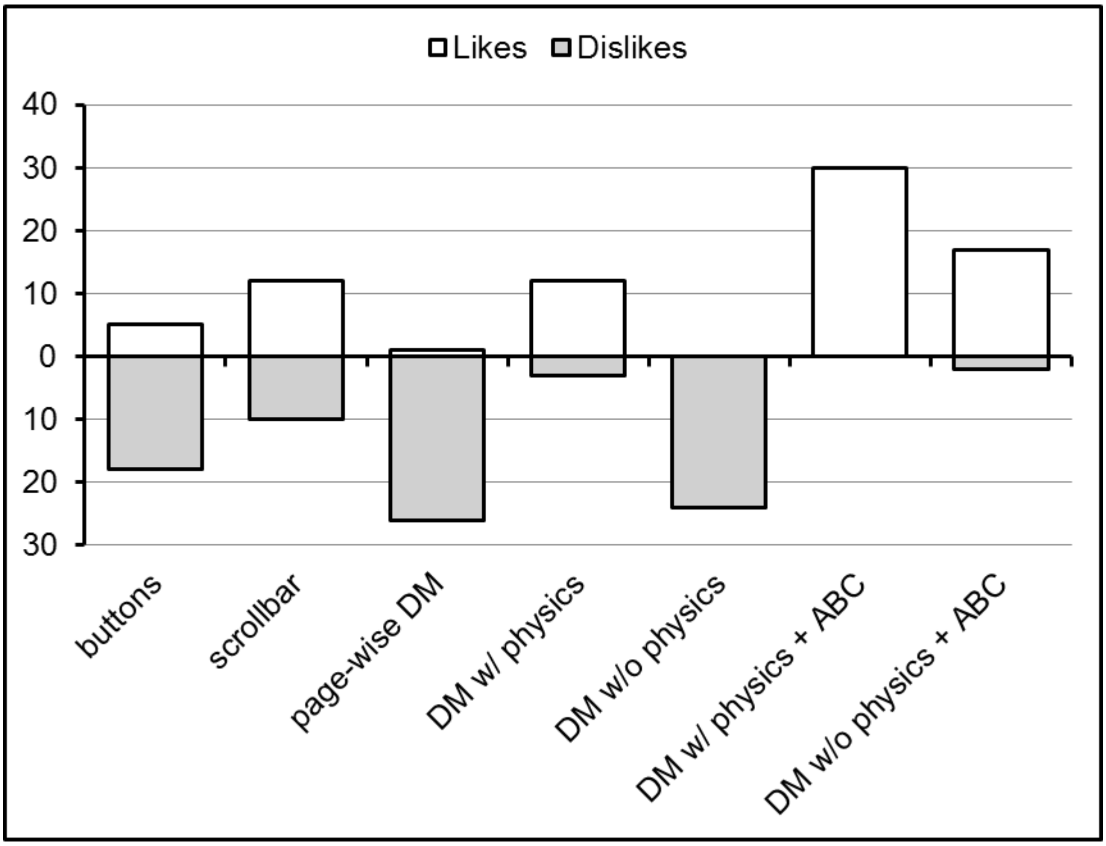

Figure 57: Number of likes and dislikes by participants for daily work with all list lengths.

The ratings of the suitability for different list lengths were analyzed with a two-way repeated-measures ANOVA. Due to the results of Mauchly's test, variant, list length, and the interaction between variant and list length had to be Greenhouse–Geisser corrected ($\chi^2(20) = 40.22$, $p < .05$, $\varepsilon = .74$; $\chi^2(2) = 11.21$, $p < .005$, $\varepsilon = .76$; $\chi^2(77) = 114.09$, $p < .05$, $\varepsilon = .61$). Variants and list length had significant effect on suitability rating ($F_{4.41, 136.69} = 56.15$, $p < .001$; $F_{1.53, 47.26} = 113.50$, $p < .001$). Variant and list length also interacted ($F_{7.26, 224.90} = 29.04$, $p < .001$). This could be seen for the scrollbar, which was rated better suited than other variants for medium and long lists, but rated relatively low for short lists (Figure 58). Differences in rating increased with list length. While there were little differences for short lists, the order matched the usability questionnaire and AttrakDiff for medium and long lists.

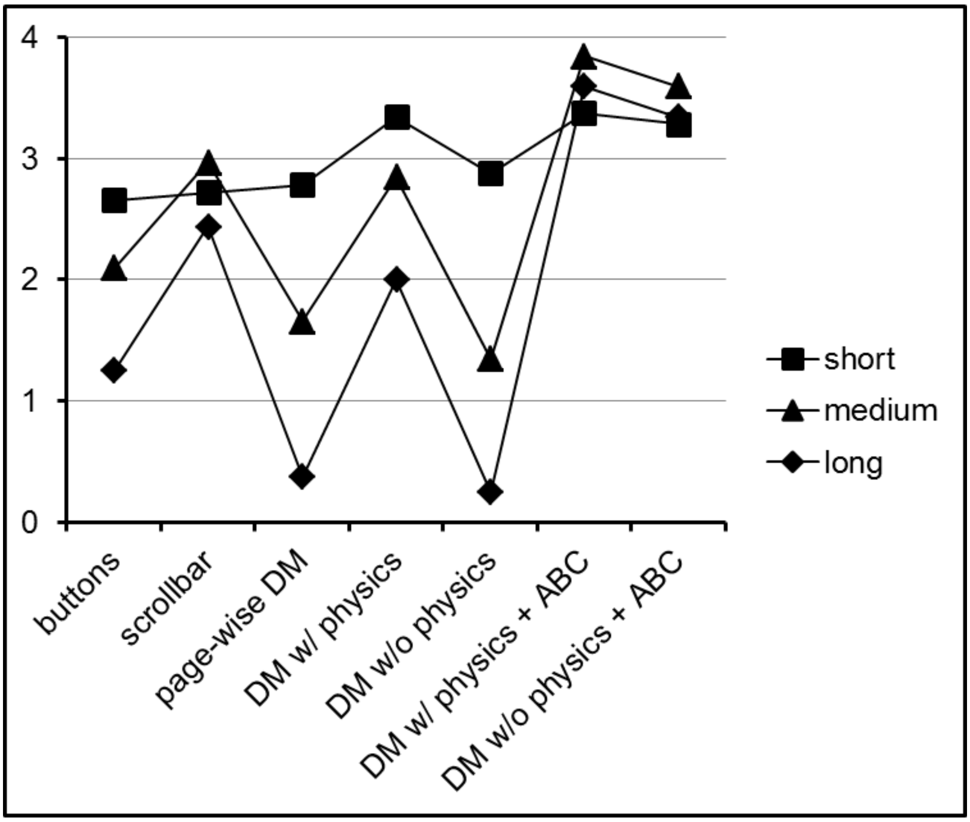

Figure 58: Avg. suitability for a certain list length. Scale ranges from "I strongly disagree" (0) to "I strongly agree" (4). While there is no significant difference between variants for short lists, the order matches the usability questionnaire and AttrakDiff scores for medium and long lists.

7.8.3.5 Evaluation of the Hypotheses

Evaluations of the hypotheses of 6.4 for the list scrolling use case:

- Hypothesis 1a: The fastest gesture-based interaction concept achieves slower task completion than the fastest tap-based one. → Direct manipulation with physics was not slower than the scrollbar or buttons. The variants with alphabetic index bar were even significantly faster. Based on these results the hypothesis is rejected.
- Hypothesis 1b: The least error-prone tap-based interaction concept has a lower error rate than the least error-prone gesture-based one. → There was no

significant difference in errors between buttons, scrollbar, and both direct manipulation concepts with alphabetic index bar. So, one could argue that this hypothesis has to be rejected. However, the scrollbar and the direct manipulation concepts with alphabetic index bar allow for use without touch gestures. If only concepts that enforce the use of touch gestures are considered (page-wise direct manipulation, direct manipulation with and without virtual physics), then they resulted in significantly more errors than the tab-based variant (buttons). The hypothesis is therefore accepted.

- Hypothesis 1c: The most popular gesture-based interaction concept is rated more favorably by users than the most popular tap-based one. → Direct manipulation with physics and alphabetic index bar was consistently rated better than buttons. The hypothesis is accepted.
- Hypothesis 2a: The fastest direct manipulation concept with virtual inertia has faster task completion than the fastest one without. → There was no significant difference between the two direct manipulation concepts with alphabetic index bar, so virtual physics seemed to have no impact on overall input speed. However, these concepts allow input without the use of touch gestures. For pure direct manipulation concepts, the variant without physics was significantly slower than the one with physics. The hypothesis is therefore accepted.
- Hypothesis 2b: The least overshooting direct manipulation concept without virtual inertia leads to less overshoots than the least overshooting one with inertia. → Direct manipulation without physics showed significantly fewer overshoots than all other concepts. The hypothesis is accepted.
- Hypothesis 2c: The least error-prone direct manipulation concept without virtual inertia has a lower error rate than the least error-prone one with inertia. → For both the concepts with alphabetic index bar and only the pure direct manipulation concepts, there was no significant difference in selection errors. The data suggests that the relation might even be opposite, although the experiment lacked power to prove the effect. The hypothesis is rejected.
- Hypothesis 3a: The fastest interaction concept with paged content has faster task completion than the fastest continuous concept. → Buttons were considerably slower than the continuous variants with alphabetic index bar. The hypothesis is rejected.

- Hypothesis 3b: The least error-prone interaction concept with paged content has a lower error rate than the least error-prone continuous concept. → While buttons had a very low error rate, it was indistinguishable from several other variants. The hypothesis is rejected.

7.8.4 Discussion

The sample is deemed representative of the working population with enough variance in age, touchscreen experience, and technical affinity. There is some evidence that the correlation between age and technical affinity in sample is also representative of the population as it has been observed by other studies (Edison & Geissler, 2003), although there are also diverging observations.

The self-assessment by the participants showed that direct manipulation concepts tend to lack feedforward, but since they are very easy to learn, this seems to have no impact on actual use.

The study showed that common list scrolling variants for touchscreen devices differ significantly in input speed, error rate, and user rating, but with a clear dependency on list length. The difference in input speed can mainly be explained with the varying motoric complexity of the variants and the number of necessary actions. On short lists, little scrolling is needed and the process of searching the right item on the screen takes most time. On medium lists, no single interaction concept was considerably superior. However, the possibility to jump near the target with the alphabetical index bar clearly accelerated task completion and it was frequently used by the participants. Although the scrollbar has the same functionality, this did not lead to an equally fast task completion. The reason might be that this functionality does not offer enough feedforward or the lack of a scale makes the jump too unpredictable for users. On long lists, the possibility to reach the target item with few interaction steps makes the variants with alphabetic index bar and, to a smaller extend, the scrollbar very fast means for scrolling. Buttons and direct manipulation with physics also reached acceptable speeds. The speed of all variants seems to correlate with the required number of interactions. Direct manipulation with physics needs several swiping gestures to reach the end of a list, but fewer than without physics because the list can be set in motion. Page-wise scrolling needs a defined number of page turns, but these are executed faster with buttons than with a touch gesture. The slow speed of page-wise direct manipulation is also partly due to the delay of the page-turning animation. In retrospect, this delay was too long and, therefore, criticized by participants. How crucial dynamic behavior for page turning is was also found by Anderson et al. (2011). The fact that the alphabetic index bar led to a speed penalty on short lists shows the importance of having the right concept for the right task. While those variants were clearly superior for long or mixed sets of lists, omission of the index bar can be advantageous if the user will only encounter short lists.

Overshooting the target item on medium and long lists was a problem encountered with all variants. However, it did not universally lead to lower efficiency. It was significantly less likely to occur when using direct manipulation without physics. On the other hand, direct manipulation without physics had a high error rate, which more than compensates for this advantage. The variants with alphabetic index bar showed a similarly low tendency for overshooting. The fact that they perform especially well on long lists could be a consequence of the fact they only show the complete alphabet if there are enough corresponding items in the list. On medium and short lists, participants might have been confused by the incomplete alphabet or just relied on direct manipulation altogether, which led to more overshoots. The reason for the frequent overshooting on the page-wise scrolling variants might be that participants did not scan every page for the target item. They could have perceived only the first few items of a page and continued scrolling until the first item's initial was after the target's initial in the alphabet. The frequent overshooting with the scrollbar can be explained with high sensitivity of the concept inherent on long lists.

Error rate, being the most important metric for critical task environments, varied highly in this experiment. While the scrollbar had an acceptable average error rate of 0.2% for all list lengths, direct manipulation without physics had an error rate of 5% overall and even 10% for long lists, making it unsuitable for any critical task environments. Given these absolute error rates, only buttons, scrollbar, and the variants with alphabetic index bar should be considered for critical task environments. Errors via unintentional selections occurred frequently when the area of interaction is the same for scrolling and selecting, like page-wise direct manipulation or direct manipulation without physics. In comparison, the error rate was very low with variants where the scrolling is initiated on a different part of the screen than the selection of the items (scrollbar, buttons, variants with alphabetic index bar). Furthermore, the risk of unintentional selections increased with the number of interaction steps (taps or gestures), which again penalizes page-wise scrolling methods and continuous variants without physics. For the buttons, the advantage of separated item selection prevails over the many necessary taps when dealing with long lists. Page-wise direct manipulation and direct manipulation without physics combine extensive interaction with coupling of scrolling and selection, which makes them rather error-prone. The addition of the alphabetic index bar addresses the second problem and decreases error rate significantly. The disproportionally high error rate on long lists when using direct manipulation without physics and alphabetic index bar might be explained in the following way: With medium lists, a single tap on the index bar is sufficient to reach the target item in most cases. On large lists, there are possibly more items beginning with the same letter than fit on screen. Thus, additional scrolling with the more error-prone direct manipulation may be necessary.

When considering the hypotheses of the experiment, it can be concluded that direct manipulation is fast and popular for list scrolling, but also error-prone, if not supplemented by virtual inertia and an index bar. The omission of virtual physics can reduce overshooting, but at the cost of slower input speed and possibly more errors. Overshooting seems to be of little importance for usability of list scrolling. Structuring list content page-wise failed to improve efficiency or error rate.

Given that the most important goal of an interaction concept in a critical task environment is a low error rate, only buttons, scrollbar, and the variants with alphabetic index bar seem suitable. The variants with alphabetic index bar are the most efficient, buttons and scrollbar are equally slower (around 30%). This leaves the popularity of the concepts as a tiebreaker to distinguish between the index variants, and buttons and scrollbar, respectively. The rating of usability and user experience by the participants matches the objective measures showing a close correlation with total task time. Therefore, both the usability questionnaire and AttrakDiff do not show a difference between the index bar variants. Nevertheless, the variant with physics should be preferred because it is in common use, while the variant without physics works differently than users might expect. The AttrakDiff score of the scrollbar is slightly better than the score of the buttons, theoretically making it the better choice. The correlation of objective usability metrics with subjective user experience metrics is consistent with finding by other researchers (Hamborg, Hülsmann, & Kaspar, 2014; Kurosu & Kashimura, 1995; Lindgaard & Dudek, 2003). Given the strong correlation, differences in attractiveness, observed by Quinn and Tran (2010) to influence user rating, seemed to have no influence, as intended in the experiment design.

In some use cases, interaction concepts with direct manipulation with physics and index bar cannot be deployed. Reasons can be e.g. the limited technical capability of the available hardware; or an environment that does not allow the safe use of touch gestures due to debris, liquids, or glove use (see 5.1.2). In this case, page-wise scrolling with arrow buttons might be an appropriate alternative with very low error rate, but slower input speed. However, users clearly preferred direct manipulation with physics and alphabetic index bar to all other variants. This differs from earlier research by Balagtas-Fernandez, Forrai, and Hußmann (2009), who observed a user preference for tabbed content, but on smaller screens. Further research could analyze new forms of scrolling like the Radial Scroll Tool by Smith and Schraefel (2004) or ChiralMotion, as described by Arthur et al. (2008). Both are similar interaction concepts, which use circular touch gestures for scrolling which eliminates rowing. They could possibly omit some of the issues of direct manipulation scrolling with physics like overshoots and unwanted selections; on the other hand, they probably need more space and have little discoverability.

7.9 Horizontal Content Change

A form of interaction that has been used as a means to navigate software dialogs in analyzed critical task environments is horizontal content change (see 6.3 and Breuninger et al., 2012). It is often used to control the functionality of large technical facilities. To access the functions across several machines, the software would mirror the technical setup with several horizontally adjacent views. This experiment was loosely modelled after such a design.

To address the high variance of display sizes in use in critical task environments, the impact of display size on different interaction forms was a secondary object of investigation. While the influence of display size has been shown by Oehl, Sutter, and Ziefle (2007) for the performance of simple pointing tasks, the relevance for touch gestures is yet unclear. Touch gesture size is affected (Popova-Dlugosch, Wenz, & Bengler, 2014), but user performance had yet to be studied.

To analyze the effects of direct manipulation and virtual physics on efficiency and error rate during horizontal content change, two usability studies of six different interaction concepts were done. The first experiment was conducted by Felix Menzel on a tablet computer with a 8.9" screen (Menzel, 2012). The second experiment was conducted by Emmanuel el-Khoury on a stationary touchscreen with a 21.5" screen (el-

Khoury, 2013). The studied variants and the procedure were identical in both studies. The chosen variants have been in use in known critical task environments or they are based on touch gestures common in consumer electronics.

The primary goal of the experiment was to test hypotheses 1a, 1b, and 1c (6.4) for the use case of horizontal content change. Moreover, hypotheses 3a and 3b can also be analyzed for this use case. The primary independent variable in this experiment was the difference between the interactions concepts. They differed in their need to be operated with touch gestures to test hypotheses 1 and in their presentation of the content, either paged or continuous, to test hypotheses 3. The properties of the individual variants are described in 7.9.1. The second independent variable in the experiment design was the size of the used screen. Half the participants used the 8.9" screen, the other half the 21.5" screen.

The dependent variable to test hypotheses 1a and 3a was the total task time, the duration it took a participant to reach the target content. To measure the error rate in order to test hypotheses 1b and 3b two metrics were observed: overshoots is the number of times a user switches to another content page after already reaching the target content. For the continuous content, it means scrolling past the target content, so it leaves the viewport. This error will not necessarily lead to unsuccessful task completion, but decrease efficiency. It is therefore a correctable error (see 3.1.2.4). The second metric is the number of navigation errors a user makes. In this experiment, a navigation error is any interaction that does not lead to an advance toward the target content. This is also a correctable error. Since content change is a means of navigation in a software system, uncorrectable input errors were not possible in this experiment. Nevertheless, the experiment design did include input tasks at each target screen to ensure a realistic task design (see 7.9.2). To test hypothesis 1c, the usability and user experience of the variants were rated by the participants. The same questionnaires as in the list scrolling experiment were used.

An a priori analysis with G*Power (Faul et al., 2007) calculated a needed sample size of 24 people for a repeated measure ANOVA with six measurements of six groups to detect a large effect ($f = .4$; probability of α error = .05; power = .95; number of groups = 6; number of measurements = 6; correlation among measures = 0; nonsphericitiy correction $\varepsilon = 1$). The large effect was expected based on preliminary tests and the experience with the preceding studies.

Like the list scrolling experiment, this experiment was designed for random participants, representative of the working population, but without knowledge about or work experience in critical task environments. The tasks were designed to be representative of tasks that occur in critical task environments without needing extensive training of the participants to gain the necessary understanding and reach realistic input speed. This was decided to limit the complexity of the experiment design and ensure a reasonable transferability of the gained insights to different use cases.

7.9.1 Variants

A fictitious machine consists of seven parts that can each be controlled by the operator. The seven parts make up a production line. They are positioned consecutively and numbered. Each machine part has different functionalities that have to activated or monitored by the operator. The variants differ in their mode of operation to reach the different parts of the machine. The possibilities to activate functions of individual machine parts are identical in all variants.

7.9.1.1 Safe Home

The Safe Home concept consists of a home screen with a row of seven buttons and a detailed machine part screen (Figure 59). The buttons on the home screen show the outlines of the machine parts and their numbers. A tap on a button will bring you to the respective machine part screen. On the detailed screen, there is an outline of the machine part and widgets to control its functions. Additionally, there is a home button on the bottom left, which allows for navigation back to the home screen. The number of the machine is displayed in the upper left corner.

7.9.1.2 Tabs

To navigate to the different parts of the machine, the navigator can tap on tabs on the bottom of the screen (Figure 60). The tabs are designed as if the active dialog was a sheet of paper with a tab on top of other sheets whose tabs can be seen next to each other without occlusion. On the tabs an outline of the respective machine and its number are shown. There are connections between the machines to allude to a production line. The tabs work exactly like known from office PCs, the only difference to most implementations is that they are on the bottom of the screen (like Excel spreadsheets) for less occlusion by the user’s hand and arm and that their touch-active area is far larger to be an easy target for the finger.

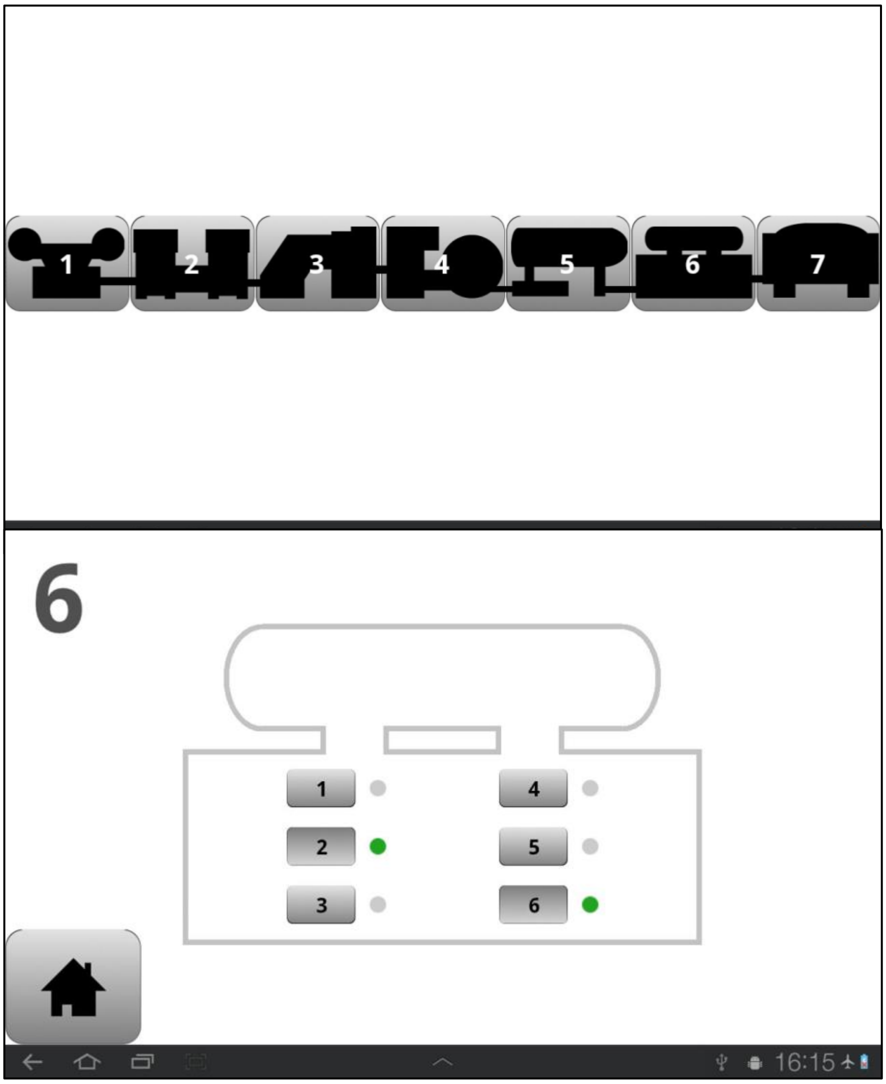

Figure 59: Implementation of the Safe Home variant

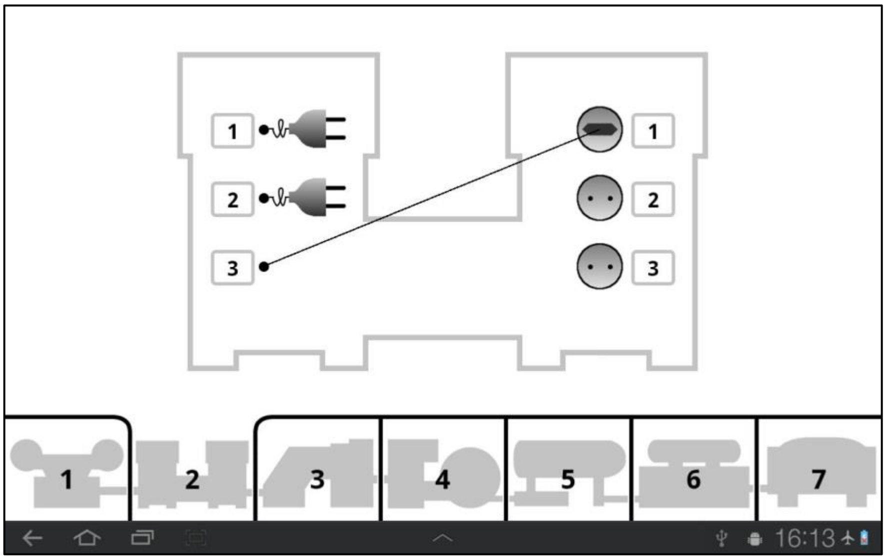

Figure 60: Implementation of the Tabs variant

7.9.1.3 Arrows

The arrows concept was identical to the tabs concept, but featured additional arrow buttons on the sides for a direct content change to the adjacent machine (Figure 61). The arrows were of the same grey as other interactive elements and had a shading to look convex as feedforward. The shading changed when pressed as if the arrow was pushed in. Although the arrows were narrow, the underlying active touch area was large enough to offer sufficient target size for accurate activation (iceberg tip button).

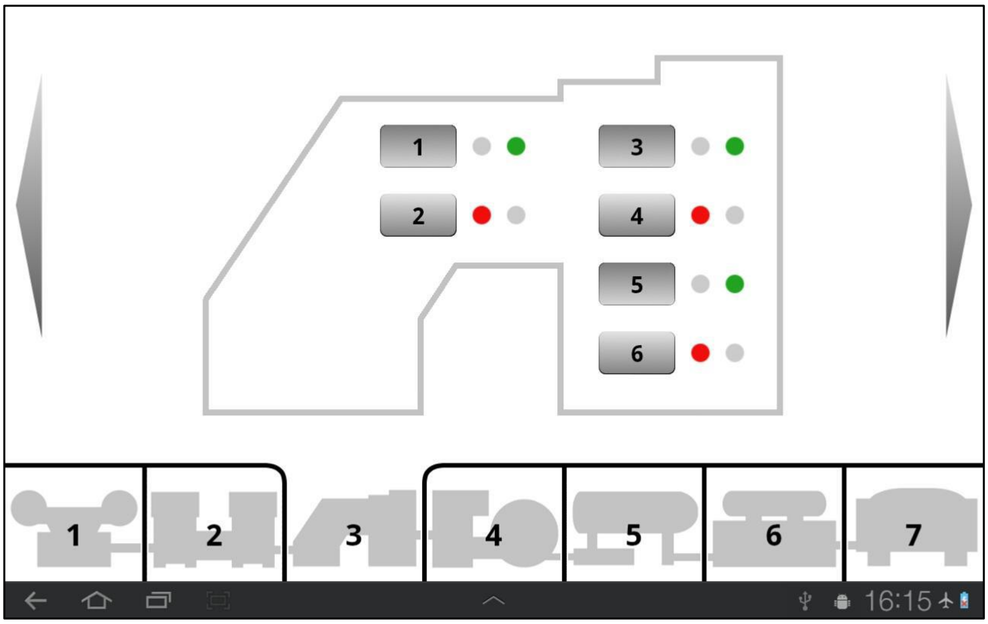

Figure 61: Implementation of the Arrows variant

7.9.1.4 Page-Flip

Page-Flip uses direct manipulation via touch gestures to change the content to an adjacent machine part with a swipe gesture on the visible machine part. The user drags the visible machine part out of the viewport to bring the next machine part into view. It is a paged interaction concept, i.e. the viewport will always adjust exactly to the next machine (virtual gravity). The transition between machines is animated matching the gesture motion to make the dragging metaphor consistently visible (Figure 62).

Additionally, there is a miniature view of all machine parts at the bottom, which allows direct switching to all machine parts. The current machine part in the main view is marked with a blue border on the miniature view. The blue border changes as soon as the dragging animation is over and the new content shows in the main view.

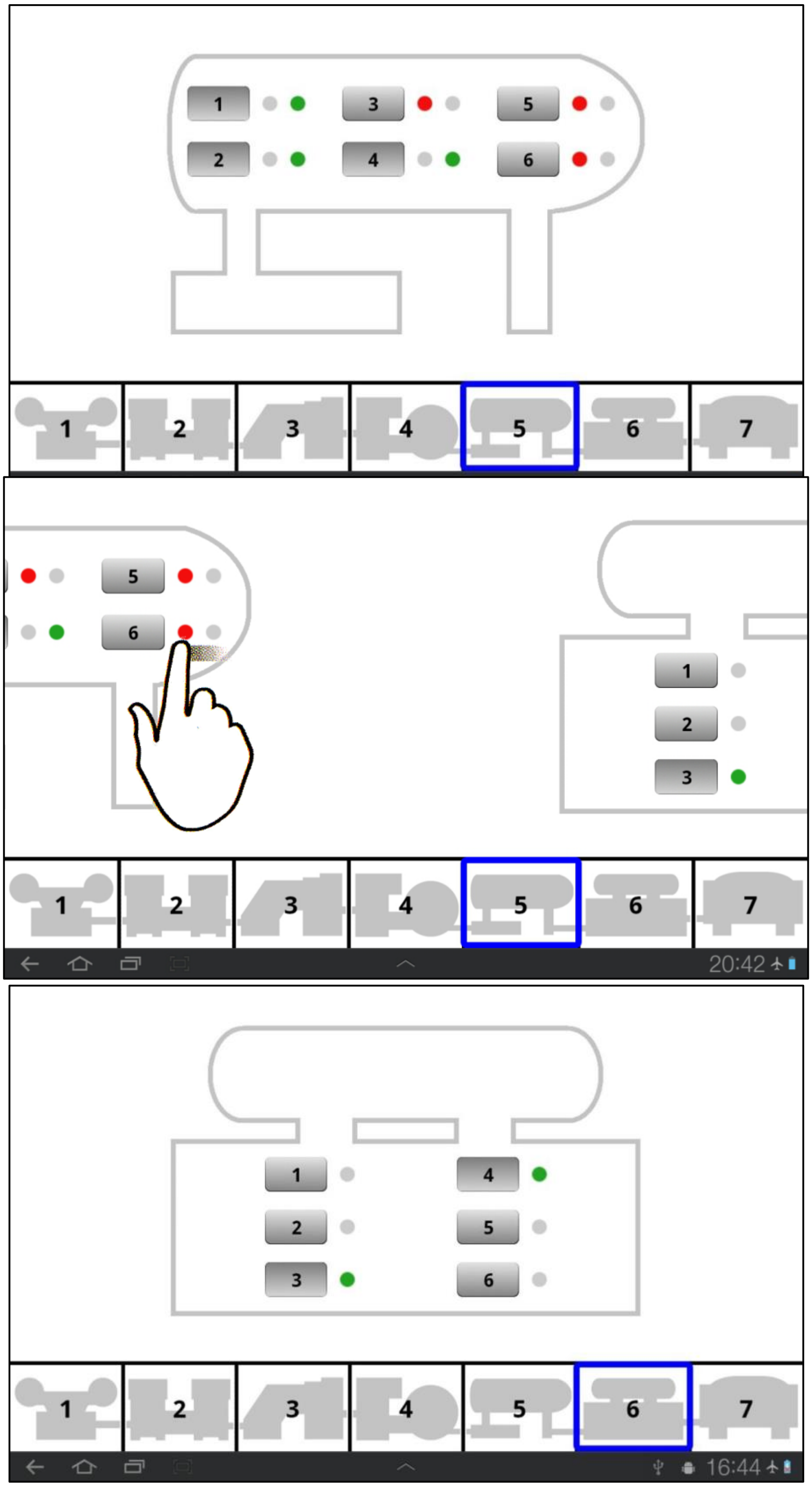

Figure 62: Implementation of the Page-Flip variant. A drag to the left switches from machine #5 to #6

7.9.1.5 Scroll

The Scroll variant is a continuous representation of the production line with a miniature view on the bottom, which works as a scroll bar. The design is similar to the Page-Flip variant; the current position is represented by a blue border. Users can drag the continuous view on top as well as tap or swipe on the scroll bar. Being continuous, the view can stop anywhere on the production line. It is not assured as in the paged variants that a whole machine part will be in the viewport. To warn when either end of the main view is reached the border will glow in blue (standard Android behavior).

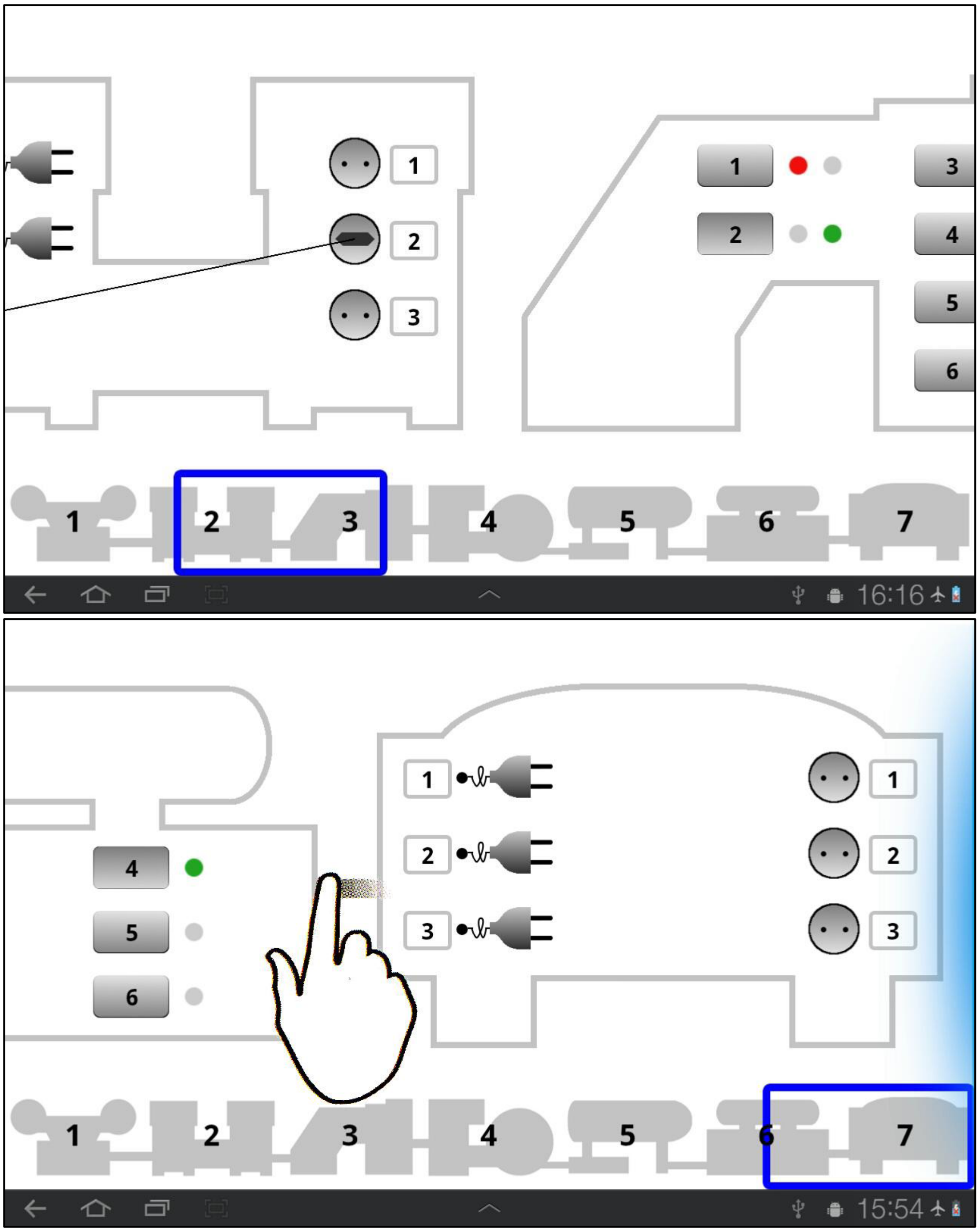

Figure 63: The Implementation of the Scroll variant

7.9.1.6 Pinch-Spread

The Pinch-Spread variant consists of an overview and a detailed view, similar to the Safe Home variant. There are no buttons to switch between the two views though. On the overview, a separation of the machine parts is only suggested with dotted borders between the parts. Users can navigate from the overview to the detailed view by executing a spread touch gesture on a machine part (or anywhere else, the most centered machine part will be chosen). Likewise, they return to the overview with a pinch gesture (Figure 64). Moreover, they can switch to the adjacent machines with swipe gesture, analogous to the Page-Flip variant. The number of the current machine part is shown in the upper left corner. This variant is an implementation of the zooming feature of many photos and maps apps on consumer electronic devices like tablets or smartphones. Both the zooming and the swiping are supported by appropriate animations.

7.9.2 Procedure

The usability studies for horizontal context change were conducted in a usability lab at the Chair of Ergonomics of Technische Universität München. Participants were instructed to perform different tasks on a fictitious machine that spread horizontally over seven software dialogs on a touchscreen device. One study used a Samsung Galaxy Tab tablet with an 8.9" screen and Android 3.2. The tablet was held in landscape mode. The other study used a PC with Windows 7 and a 21.5" Iiyama ProLite T2233MSC touchscreen. The participants had to operate the tablet and the stationary touchscreen while standing. This was in order to simulate the posture and physical load of touchscreen interaction in an industrial environment. During the experiment, the interaction with the touchscreen was recorded from above or from behind, respectively (Figure 65, Figure 66, Figure 67). An experimenter instructed the participants and was present in the same room, though separated from the participants by a screen during the task completion.

Each participant had to get to know each variant and to use it to fulfill several navigation tasks. The task would include navigating to a specified machine part and activating a function there. Functions were activated with toggle buttons, radio buttons, dropdown lists (Figure 68), a drag of a box onto another box, or a drag of a plug into an outlet (Figure 69).

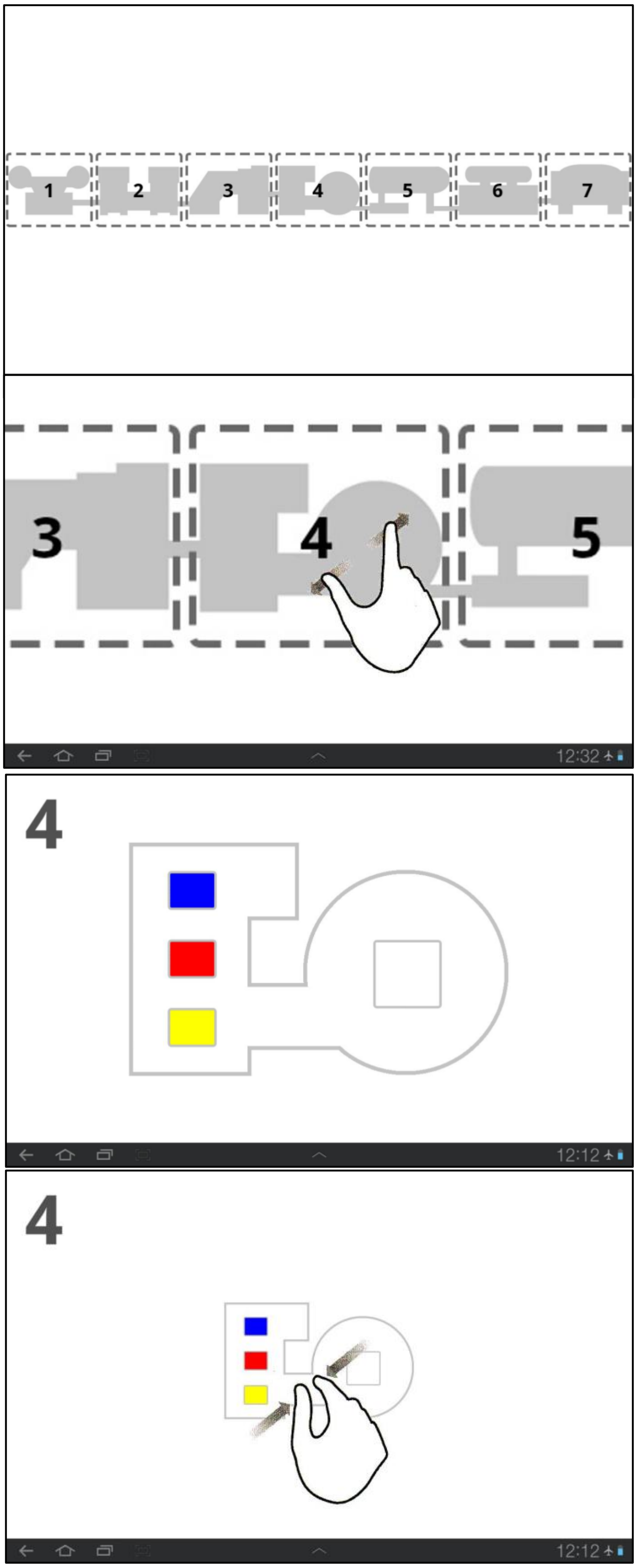

Figure 64: Implementation of the pinch–spread variant. Spreading on an outline in the overview will zoom in on the machine part. Pinching on the detailed view will zoom out.

Figure 65: A Participant in the usability vab during the tablet study

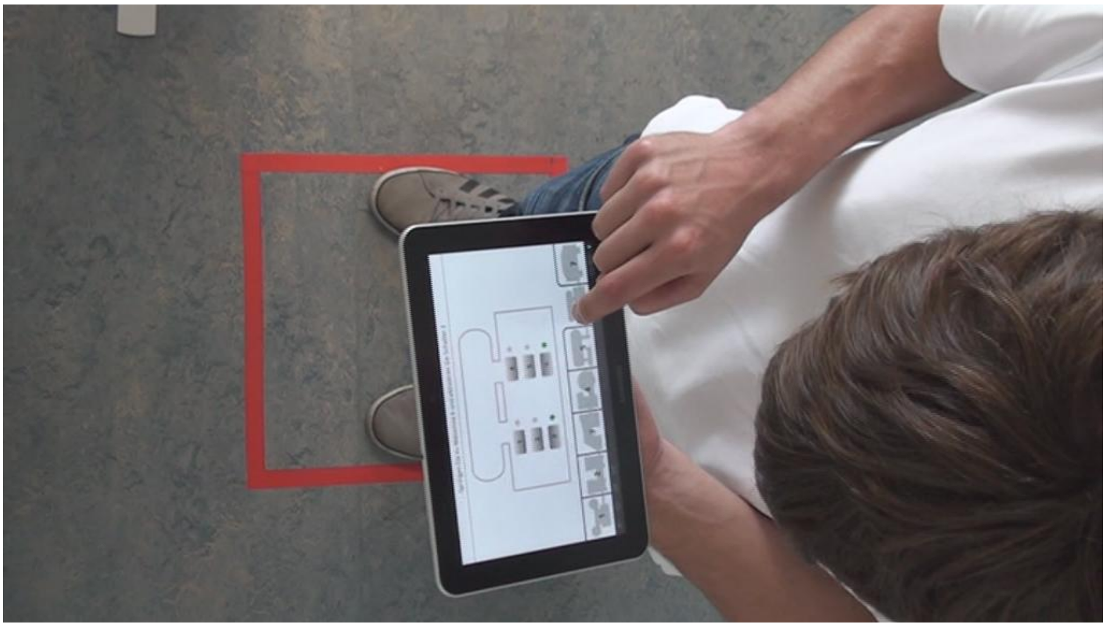

Figure 66: Camera picture from above in the tablet study

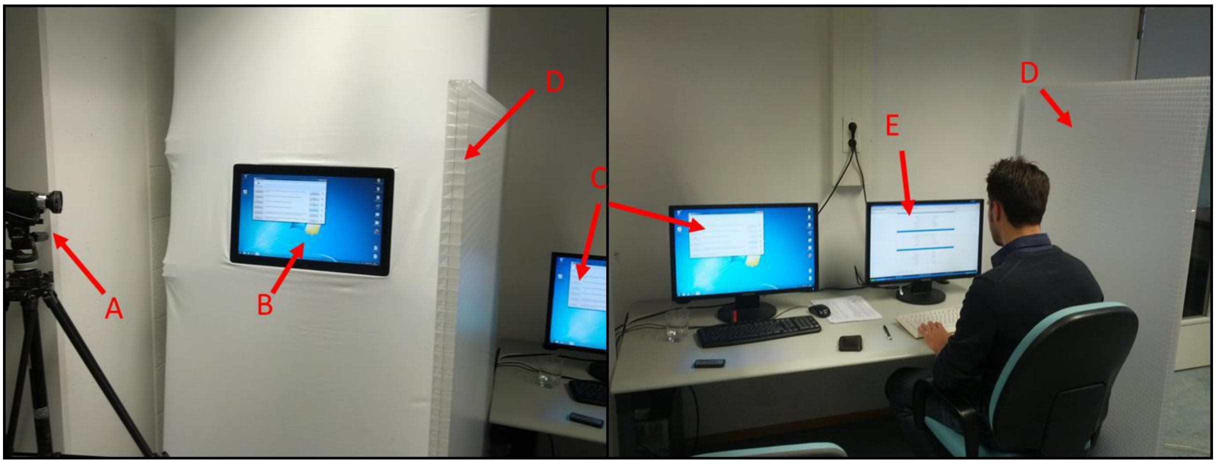

Figure 67: Participant in the usability lab during the stationary touchscreen study. Camera (A), touchscreen (B), experimenter's control PC (C), screen (D), questionnaire PC (E)

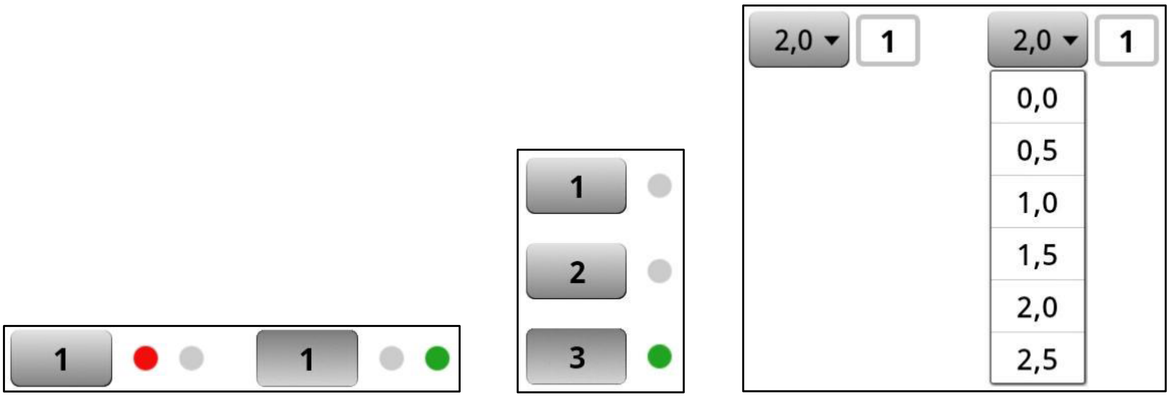

Figure 68: Widgets for user tasks: toggle buttons, radio buttons, dropdown lists

After being presented a variant, the participant was instructed to try it out until he or she felt comfortable using it and had understood all its features. If a method of interaction remained undiscovered by the participant, this was documented. The experimenter explained the full functionality of the interaction concept and the participant was again given time to try it out. This was repeated with all six variants. Participants were presented the variants in random order.

After the initial try-out phase, tasks had to be solved with the different variants. The variants were presented in the same order as before. Participants were instructed to solve the presented tasks promptly, but with precision, as if it was their daily job. No time budget was defined or enforced to simulate a work environment with some, but no immediate time pressure (compare 7.8.2). All uses of horizontal content change that had been observed at industrial environments did not rely on being performed within a defined time frame (Breuninger et al., 2012).

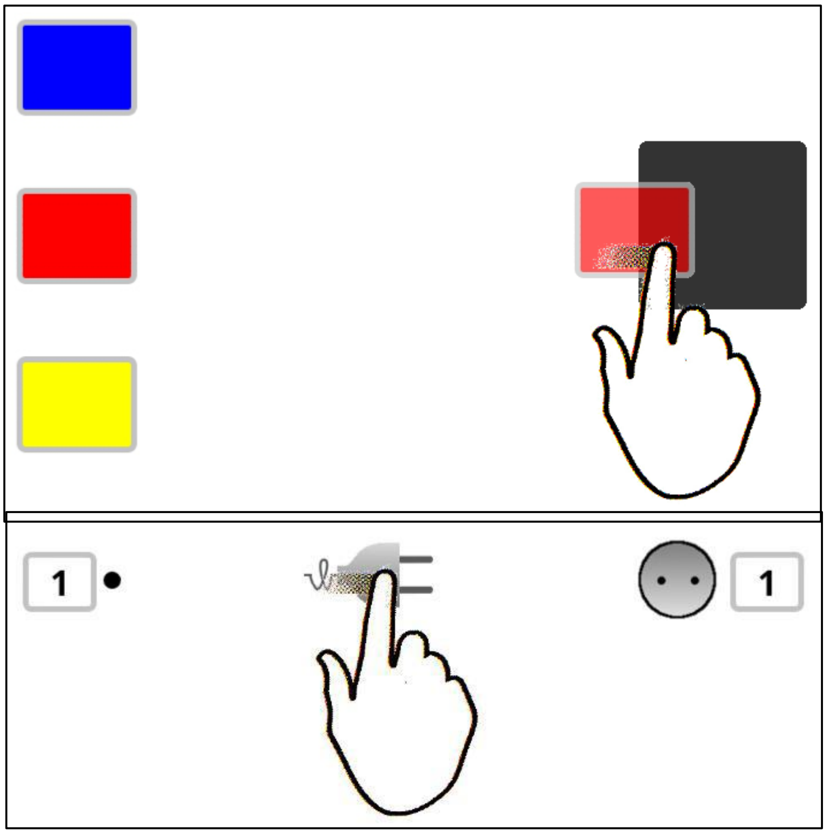

Figure 69: User tasks: Dragging a box onto another box; dragging a plug into an outlet.

After pressing a start button, the participant was presented a text box with the instruction for the current task (Figure 70). The instruction had to be confirmed by pressing OK to start the task. The instruction was shown additionally at the top of the screen as long as the task was not finished (Figure 71). Each task was to navigate to a part of the machine and press buttons or perform a drag and drop task there. After completion of a task, visual and acoustic feedback was given and a new instruction text box was displayed.

Each participant had to solve eight tasks with each variant. Each possible distance between machine parts occurred at least once, distance 1 (adjacent) and 3 occurred twice. To avoid learning effects (Bortz & Döring, 2006), there were six different sets of tasks that were randomly assigned to each variant for each participant. After completion of all eight tasks with the same variant, participants answered questionnaires. As in the study for list scrolling, these were the same custom usability questionnaire and the AttrakDiff 2. This procedure was repeated five times to examine all six variants. After the last variant, participants completed an additional questionnaire to choose their favorite and least favorite variant. A flowchart of the procedure is shown in Figure 72.

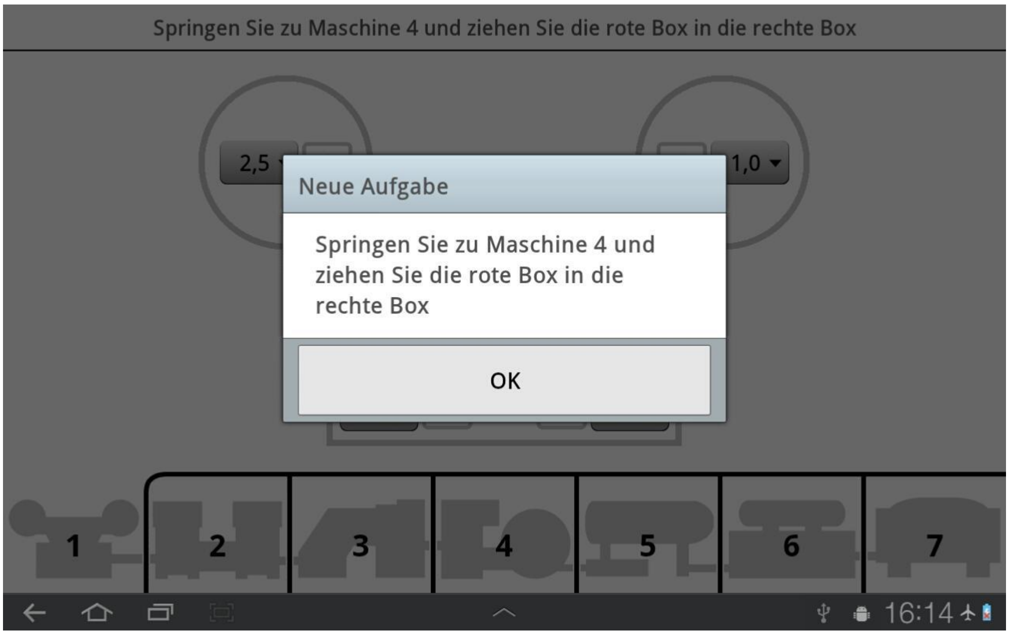

Figure 70: Instruction text box ("New task. Go to machine #4 and drag the red box into the box on the right.")

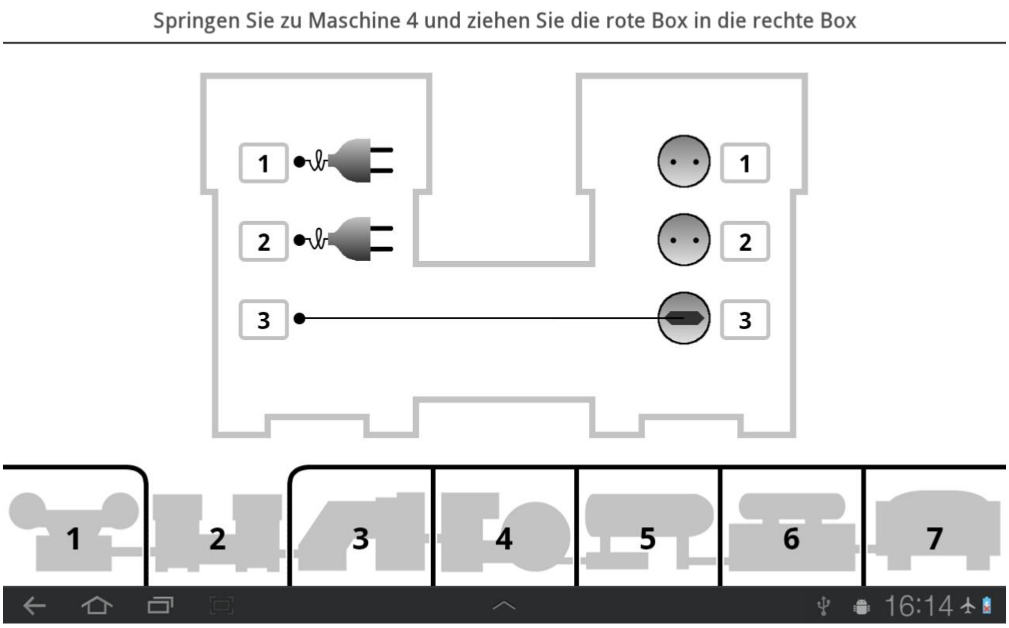

Figure 71: User interface during task solving. Instructions are at the top.

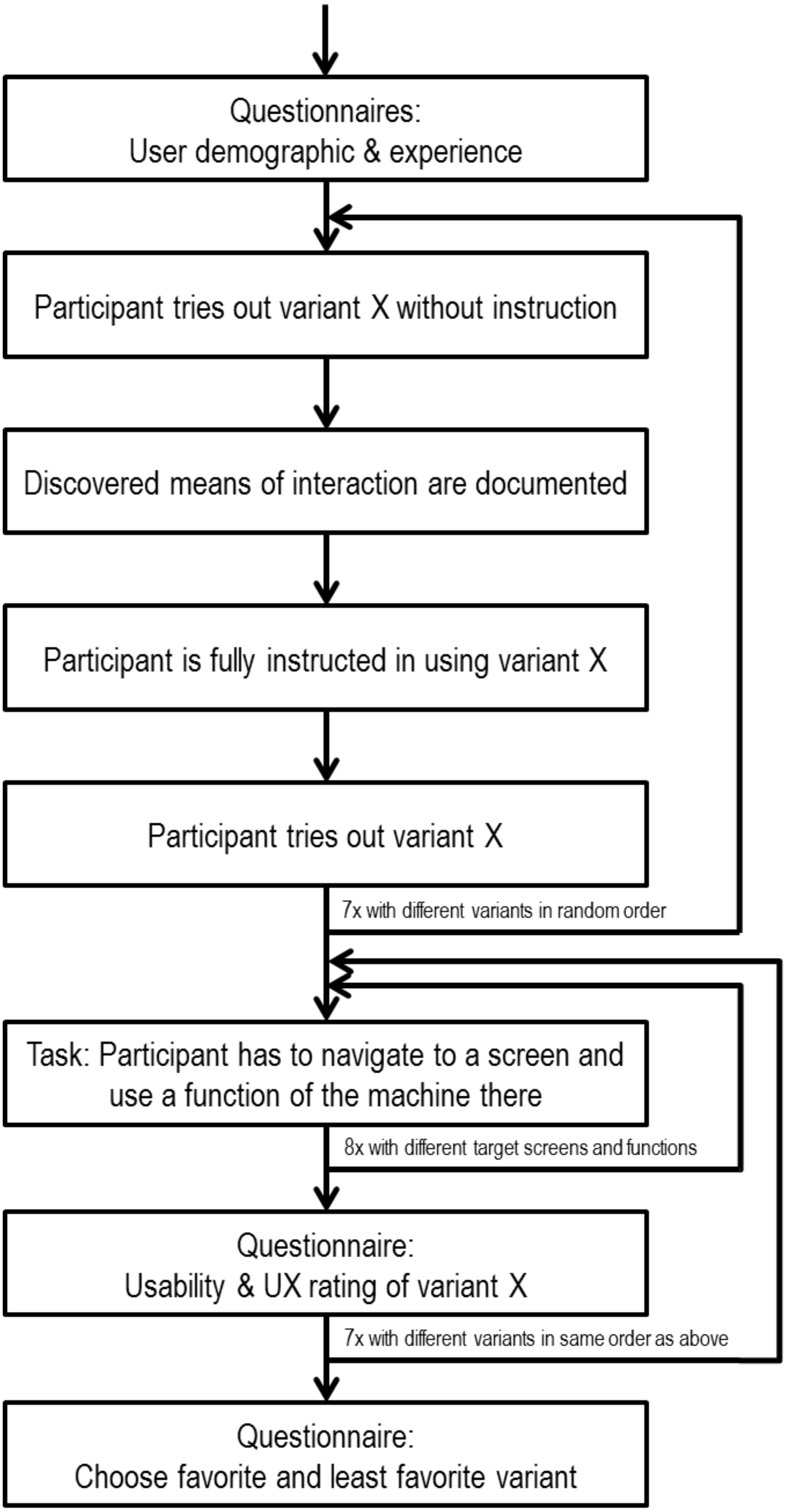

Figure 72: A flow chart of the steps each participant had to go through in the experiment for horizontal content change

7.9.3 Results

Thirty people voluntarily participated in the study using the tablet computer (19 male, 11 female; age 22–70, M = 34.0, SD = 13.1). Another thirty people voluntarily participated in the study using the stationary touchscreen (23 male, 7 female; age 18–26, M = 21.9, SD = 13.1). Thus, the combined sample of both studies was sixty people (42 male, 18 female; age 18–70, M = 27.8, SD = 13.1). Due the lower average age of participants in the second study, there was a significant medium correlation between screen size and age ($r = .45$, $p < .001$). Almost all participants had some experience with touchscreen devices (Figure 73). Many regularly used smartphones and sometimes tablets and navigation systems. Participants scored an average of 2.98 on the TA-EG questionnaire for technical affinity (SD = .45).

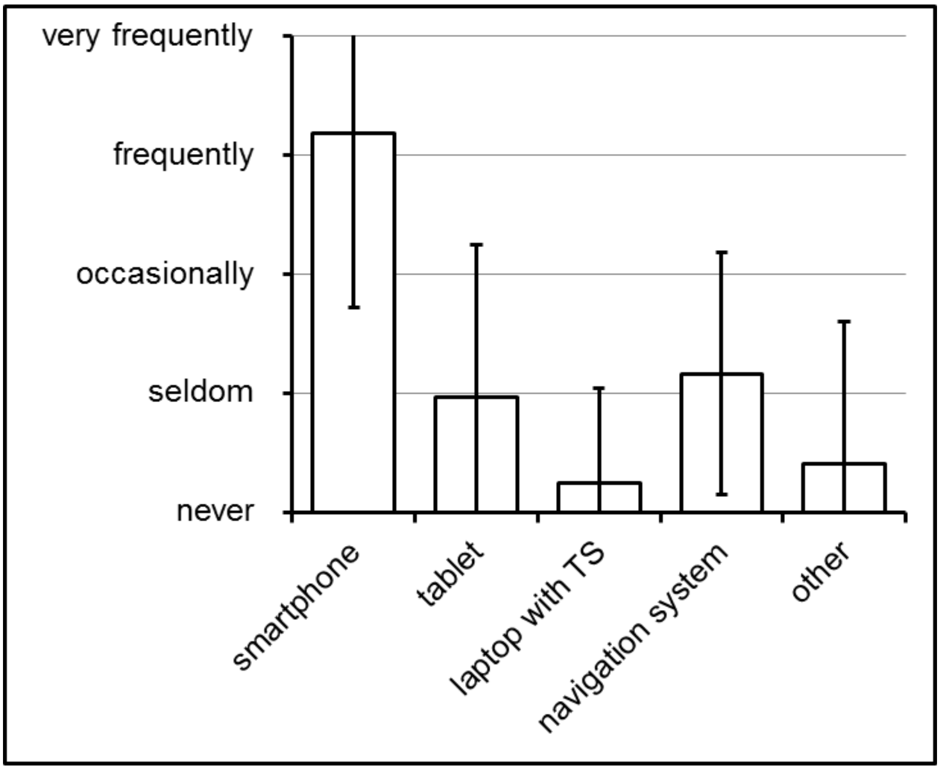

Figure 73: Average participant experience with touchscreen devices. Error bars show ± 1 standard deviation.

The men in the sample were slightly younger than the women ($r = -.30$, $p < .05$). On average, older participants had slightly less overall touchscreen experience ($r = -.17$, $p = .25$). There was a significant correlation between age and smartphone use ($r = -.34$, $p < .005$). The technical affinity of the participants only correlated very little with their age ($r = -.15$, $p = .25$). Female participants showed slightly more frequent smartphone use ($r = .21$, $p = .22$), more experience with touchscreen devices ($r = .16$,

$p = .22$) and higher technical affinity ($r = .26$, $p < .05$). There was a significant medium correlation between the participants' overall touchscreen experience and their technical affinity ($r = .40$, $p < .005$). In contrast to the list scrolling study, the correlation between smartphone use and technical affinity was small and not significant ($r = .14$, $p = .30$).

7.9.3.1 Total Task Time

There were considerable differences in total task time between the interaction variants. Total task time is the time it takes the user from acknowledging the instruction dialog to reaching the correct machine screen. The time it takes to solve the task there is not taken into account for this metric. A factorial mixed design ANOVA was used to determine if significant difference in total task time between variants occurred (Field, 2005). The six variants were the within-subject factor and the display sizes were the between-subject factor.

Mauchly's test revealed that the assumption of sphericity in the data had been violated for the effect of the interaction concept: $\chi^2(14) = 59.4$, $p < .001$. Degrees of freedom were reduced with Greenhouse–Geisser correction: $\varepsilon = .67$. The interaction concept had significant effect on total task time ($F_{3.34,\ 193.8} = 53.17$, $p < .001$).

Tabs and Arrows were the fastest concepts, although Arrows could not be distinguished from Page-Flip (Figure 74) by the Bonferroni post-hoc test. Scroll was slower than Tabs and Arrows, but faster than Pinch–Spread, which was slowest. Safe Home was faster than Pinch–Spread, but slower than the Tabs, Arrows, and Page-Flip. The paged concepts Tabs, Arrows, and Page-Flip all performed better than the continuous Scroll. The fastest concepts with touch gestures, Page-Flip and Scroll, both performed slower than the fastest variant without, Tabs.

Display size had no significant effect on total task time ($F_{1,\ 58} = .27$, $p = .61$).

Details on the statistical analysis of total task time can be found in appendix A.

7.9.3.2 Overshooting

Overshooting is an error that occurs when the user navigates to the target view, but continues in the same direction to the adjacent view. This kind of error is not possible with the Safe Home and Tabs variant because they do not allow a horizontally directed switch to adjacent views. Overshooting errors happened rarely in the study (Figure 75). Participants encountered on average .75 overshooting errors in the whole study. Only four participants made three overshoots overall, one with one variant, the others with three different ones.

Since Safe Home and Tabs both had a mean and standard deviation of zero, there is local circularity. This means “the sphericity assumption has been met for any multiple comparisons involving these conditions” (Field, 2009, p. 460). Nevertheless, differences were also significant with Greenhous–Geisser correction for nonsphericity ($\varepsilon = .64$).

The choice of interaction concept had a significant effect on the number of overshoots ($F_{3.19,\ 185.1} = 14.1$, $p < .001$). According to Bonferroni post-how tests, when using the Arrows concept, participants encountered significantly more overshoots than with all other variants. The occurrence of overshoots with the Scroll variant was frequent enough to be considered higher than with Safe Home and Tabs.

The display size had a significant effect on the number of overshoots ($F_{1,\ 58} = 26.4$, $p < .001$). Only seven overshoots occurred on the tablet, 38 on the stationary touchscreen. An explanation for this will be discussed below.

There was no significant correlation between total task time and overshoots ($r = -.31$, $p = .55$).

Details on the statistical analysis of overshoots can be found in appendix A.

7.9.3.3 Error Rate

In this study, errors are considered user inputs that do not lead to the target view. On average users made less than one error with each variant. Despite this rare occurrence and the following high variance, there were significant differences between error rates of the variants ($F_{1.18,\ 104.4} = 10.6$; Mauchly’s test showed violation of sphericity: $\chi^2(14) = 221.3$, $p < .001$; therefore Greenhous–Geisser reduction of degrees of freedom: $\varepsilon = .36$). Safe Home and Tabs showed fewer errors than the other concepts except Scroll (Figure 76), although Tabs could not be distinguished from Arrows. The uncertainty regarding Scroll errors was mainly due to the very high variance of Scroll errors because one participant had 15 errors with Scroll.

Display size had no significant effect on error rate ($F_{1,\ 58} = .25$, $p = .62$).

There was no statistically significant correlation between overshoots and error rate ($r = .41$, $p = .42$). The correlation between total task time and error rate in the sample was also not statistically significant ($r = .26$, $p = .62$).

Details on the statistical analysis of error rate can be found in appendix A.

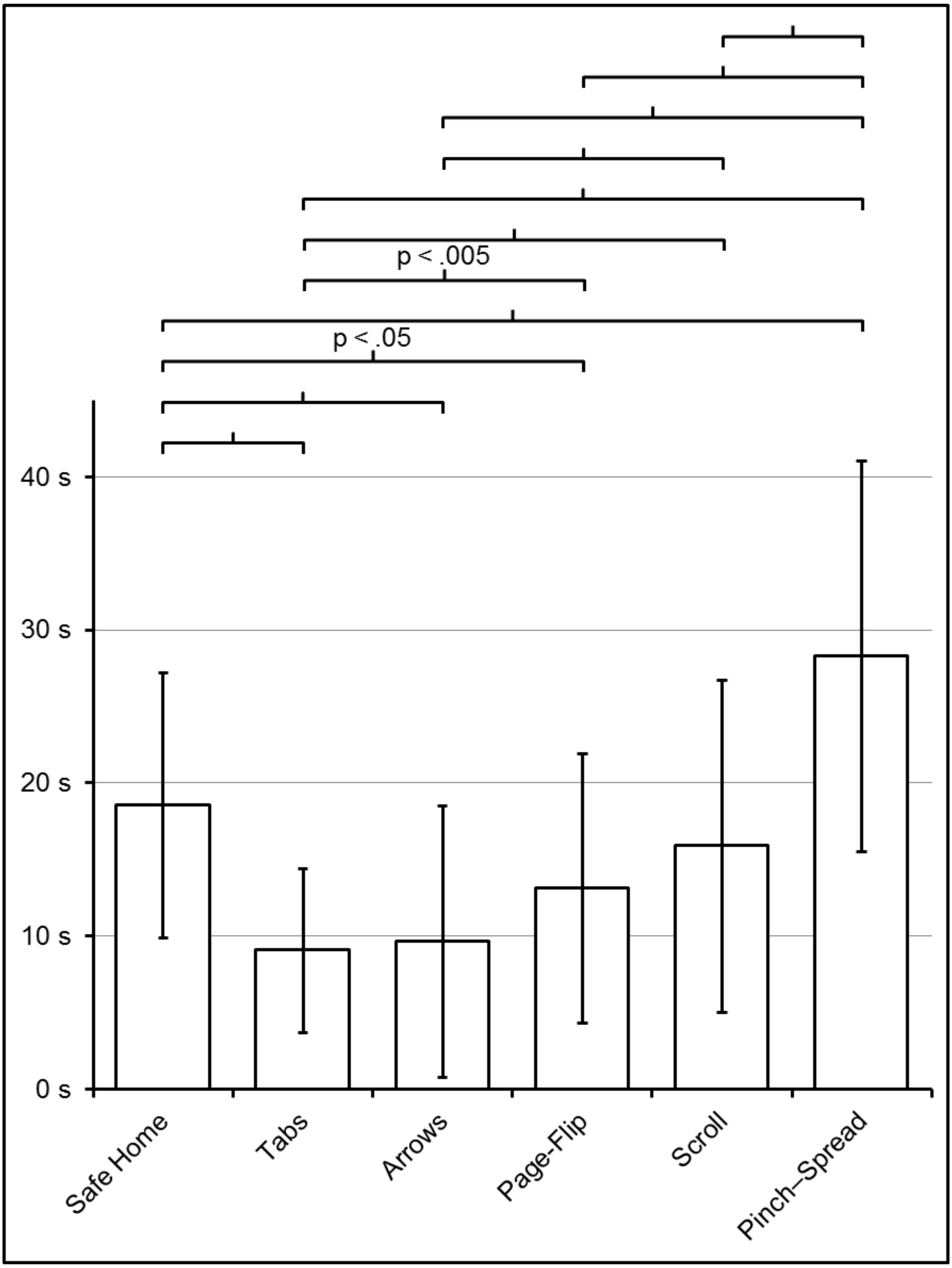

Figure 74: Total task time for navigating to the target content. Variants connected by brackets are significantly different ($p < .001$, unless the significance level is stated explicitly). Error bars show ± 1 standard deviation.

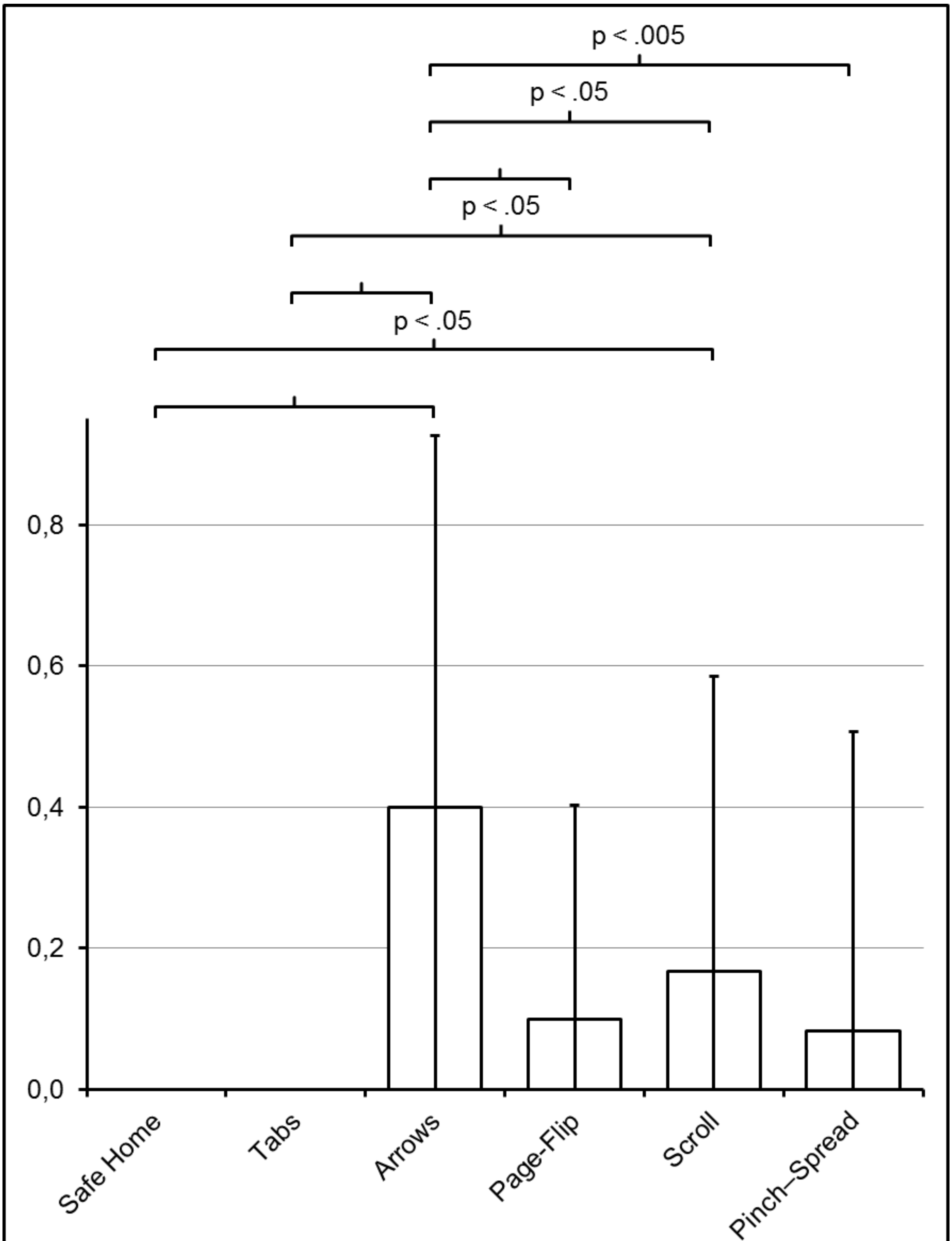

Figure 75: Average number of overshoots during eight tasks (average distance between start and target screen: 3). Overshoots are navigation steps away from the target to another adjacent view. Overshooting is not possible with the Safe Home and the Tabs variant. The relatively high mean and variance of the Arrow variant is probably caused by poor software optimization in the experiment. Variants connected by brackets are significantly different ($p < .001$, unless the significance level is stated explicitly). Error bars show ± 1 standard deviation.

7.9.3.4 User Rating

The usability of the variants was rated differently according to a factorial mixed design ANOVA ($F_{3.42,\ 198.09} = 62.97$, $p < .001$). The degrees of freedom were corrected due to Mauchly's test ($\chi^2(14) = 82.88$, $p < .001$, Greenhous–Geisser correction for nonsphericity $\varepsilon = .68$). According to Bonferroni post-how tests, Pinch–Spread and to a lesser extend Safe Home were rated worse than the other variants (Figure 77). This mirrors the total task time, but without the statistical differences between Tabs, Arrows, Page-Flip, and Scroll. Display size had no effect on usability rating ($F_{1,\ 58} = .29$, $p = .59$). For the differences between AttrakDiff scores, Mauchly's test was also violated ($\chi^2(14) = 33.11$, $p < .005$), so degrees of freedom were adjusted using Greenhouse–Geisser correction ($\varepsilon = .82$). The result shows that the variant significantly affected AttrakDiff score ($F_{4.08,\ 236.71} = 38.61$, $p < .001$). The lack of difference between the top four variants was identical to the usability questionnaire, but there was no significant difference between the trailing Safe Home and Pinch–Spread (Figure 78). Display size had no effect on AttrakDiff scores ($F_{1,\ 58} = 1.04$, $p = .31$).

The results of the usability questionnaire correlated very strongly with total task time ($r = -.96$, $p < .005$). The correlation of the AttrakDiff scores was slightly lower, but still statistically significant ($r = -.79$, $p < .05$ 1-tailed). User rating showed no significant correlation with overshoots ($r = .30$, $p = .29$ with usability; $r = .39$, $p = .23$ with AttrakDiff) or with error rate ($r = -.04$, $p = .47$ with usability; $r = .29$, $p = .29$ with AttrakDiff).

When asked which variant they would prefer for use in a work environment, most participants chose Tabs (14), Arrows (19), or Page-Flip (18) (Figure 79). Scrolling was also favored by some (9), while the slower indirect variants were exclusively chosen as least favorite. Safe Home was chosen by 13. By far the least popular variant was Pinch–Spread, chosen by 42 participants.

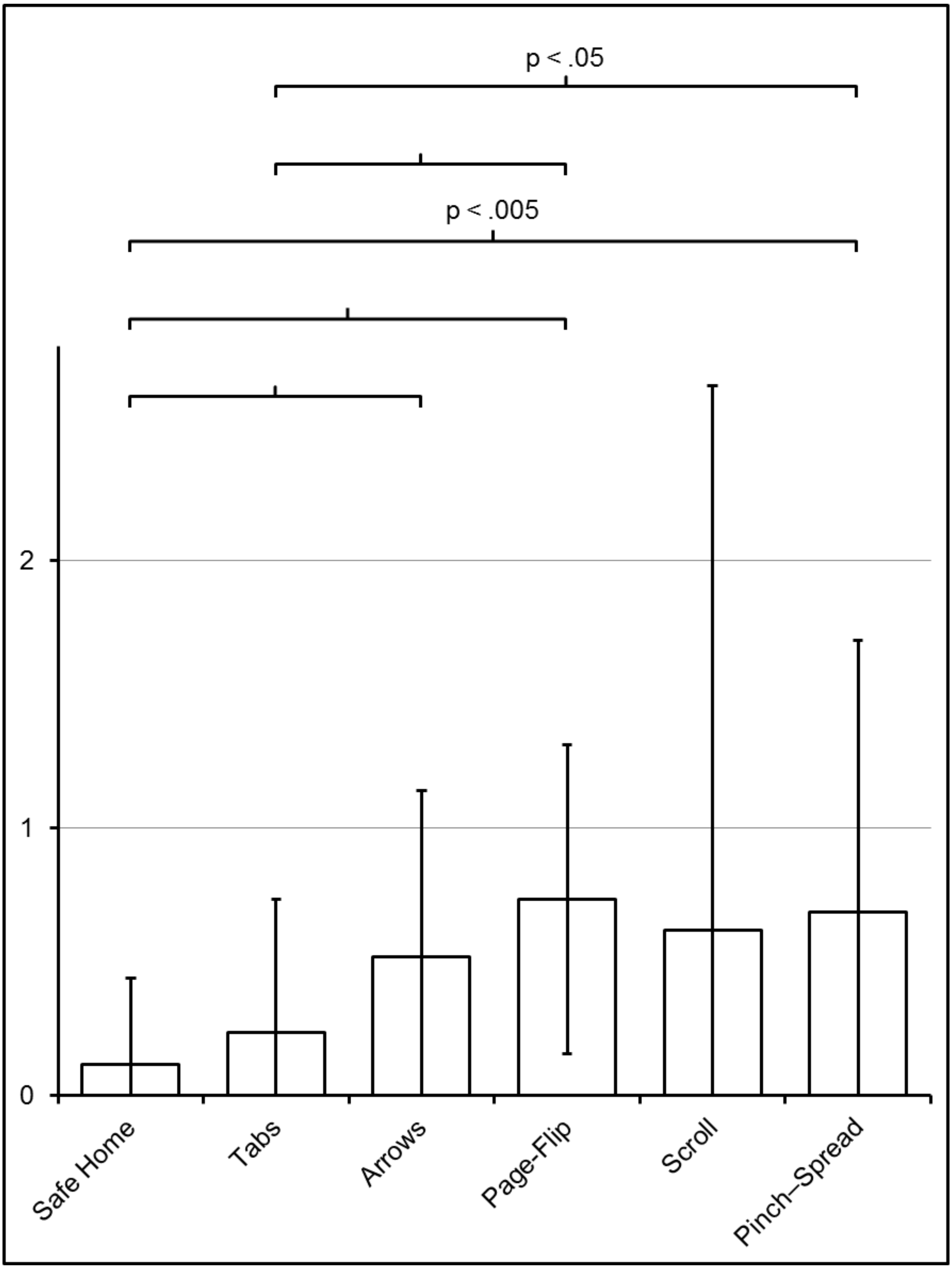

Figure 76: Average number of errors during eight tasks (average distance between start and target screen: 3). Errors are all inputs that do not contribute to navigating to the target view. This includes the overshoots. Variants connected by brackets are significantly different ($p < .001$, unless significance level is stated explicitly). Error bars show ± 1 standard deviation.

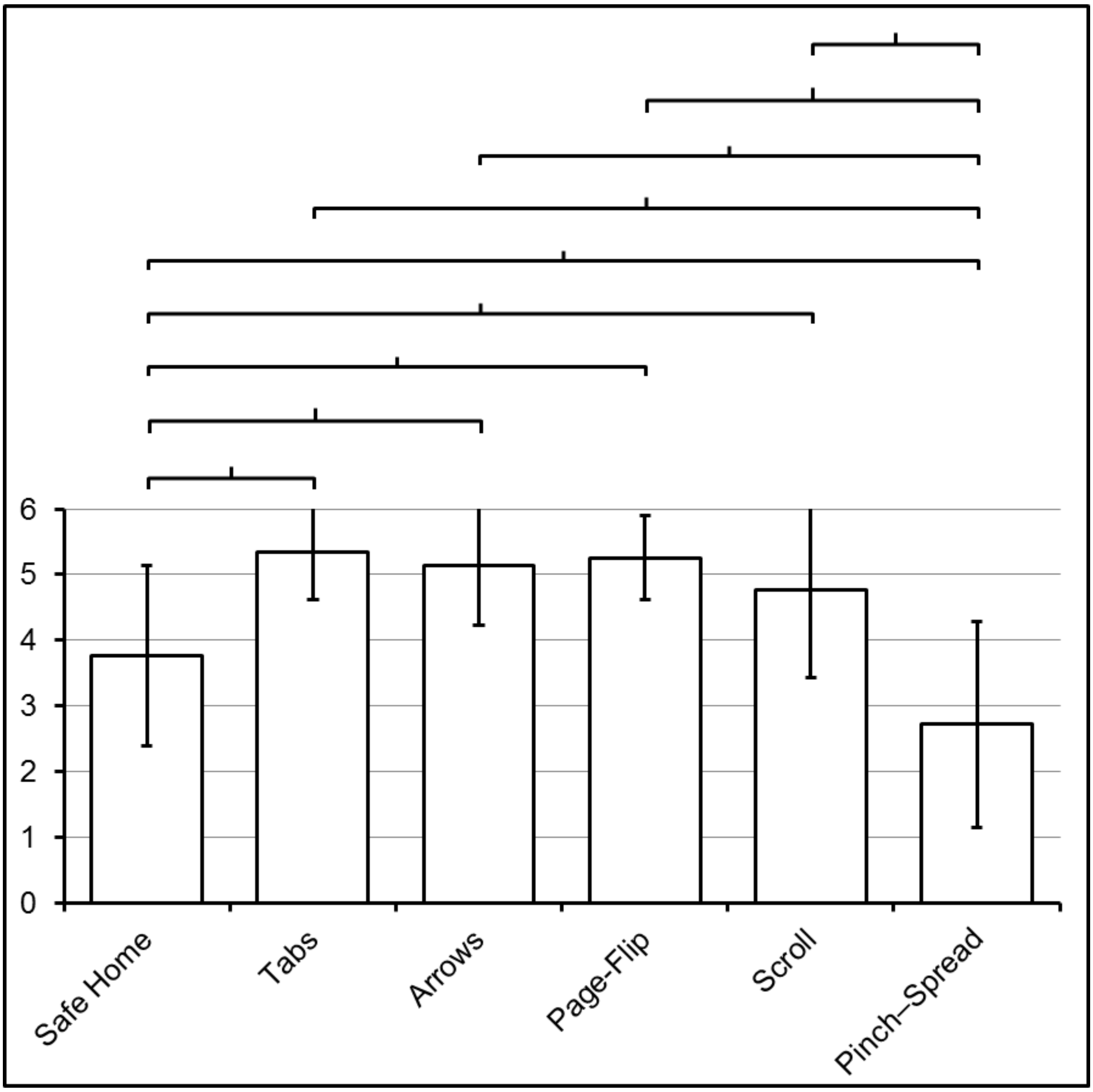

Figure 77: Avg. usability questionnaire score. Scale ranges from "I strongly disagree" (0) to "I strongly agree" (6). Variants connected by brackets are significantly different ($p < .001$). Error bars show ± 1 standard deviation.

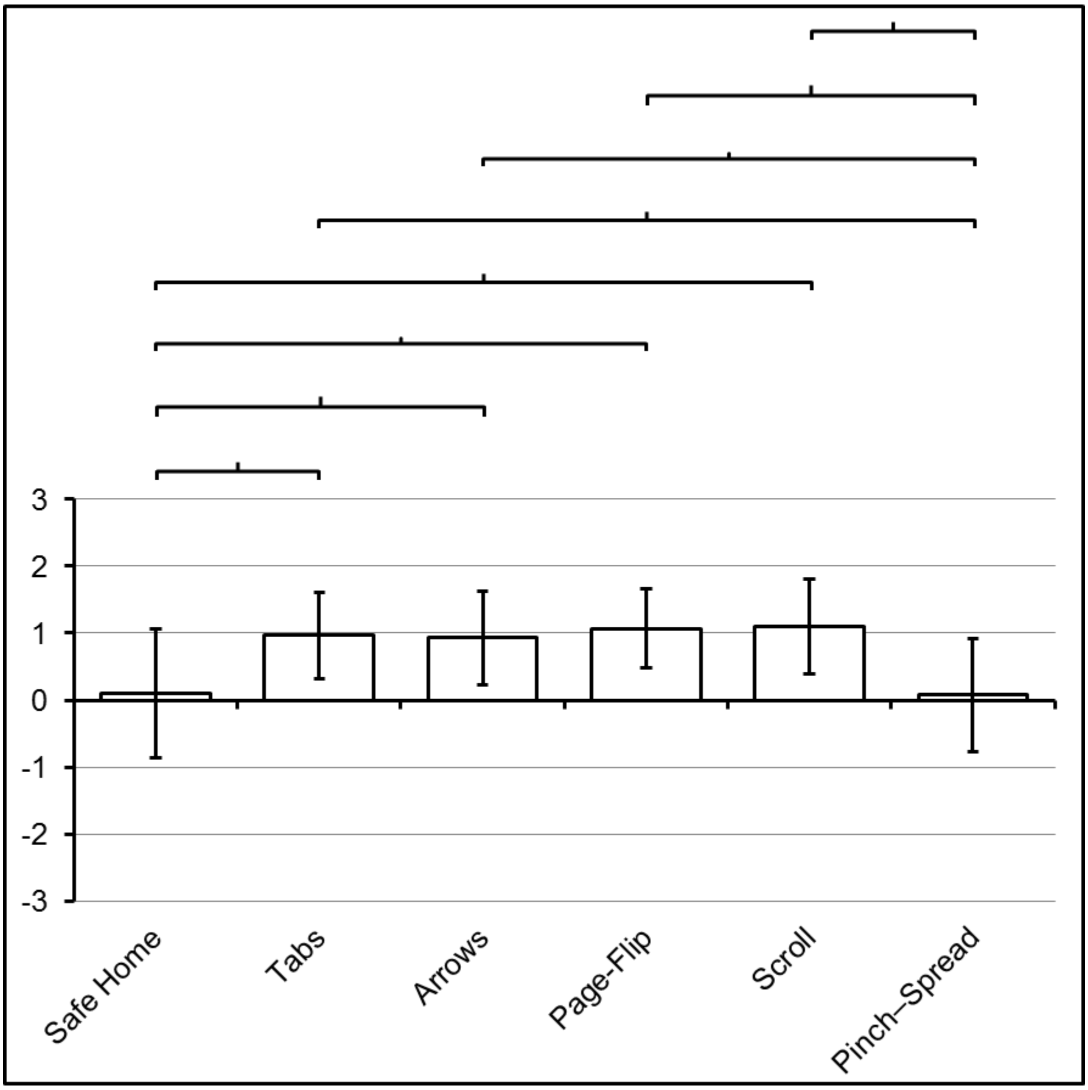

Figure 78: Avg. AttrakDiff scores. Variants connected by brackets are significantly different ($p < .001$). Error bars show ± 1 standard deviation.

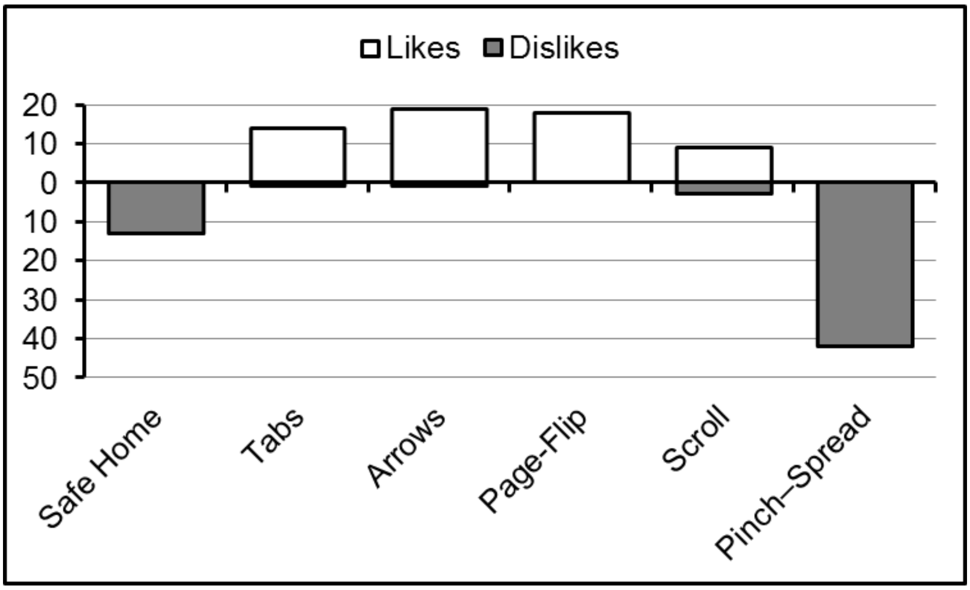

Figure 79: Number of likes and dislikes by participants for use in a work environment.

7.9.3.5 Evaluation of the Hypotheses

Evaluations of the hypotheses of 6.4 for the horizontal content change use case:

- Hypothesis 1a: The fastest gesture-based interaction concept achieves slower task completion than the fastest tap-based one. → Tabs performed significantly faster than Page-Flip. The hypothesis is accepted.
- Hypothesis 1b: The least error-prone tap-based interaction concept has a lower error rate than the least error-prone gesture-based one. → Due to the high variance of Scroll errors, there was no significant difference between Safe Home and Scroll. The hypothesis is rejected.
- Hypothesis 1c: The most popular gesture-based interaction concept is rated more favorably by users than the most popular tap-based one. → Tabs and Arrows were on par with Page-Flip, showing no significant difference. The hypothesis is rejected.

7.9.4 Discussion

The sample is deemed representative of the working population with enough variance in age, touchscreen experience, and technical affinity. Although the participants in the large touchscreen study were younger than those in the tablet study, the results are still deemed valid. Based on the experience with the list scrolling study and other prior studies by the author, age seems not to interact with different interaction concepts for usability metrics. The correlation between age and technical affinity that had been observed in the list scrolling sample was also present in this study. This further solidifies the assumption that this correlation is representative of the working population (see 7.8.4).

This study showed that variants for horizontal content change on touchscreen devices differ significantly in input speed, error rate, and user rating. The difference in input speed can be explained with the varying motoric complexity of the variants and the number of necessary actions. This is consistent with the list scrolling study. Tabs and Arrows allow for a very quick content change with a single interaction, the tap, which also has the lowest motoric complexity. Page-Flip and Scroll use touch gestures and were therefore slightly slower. Scroll has a higher complexity because it requires more precision to navigate continuous content than paged content. As expected, Safe Home and Pinch–Spread were penalized for always requiring an additional step to the overview before navigating to the target screen. Pinch–Spread additionally requires the most complex touch gesture, leading to a considerable increase in total task time.

Overshooting the target screen happened rarely in this study, so it seems to be less problematic than expected. Just like in the list scrolling study, there seems to be no correlation of overshooting with total task time or error rate. The occurrence of most overshoots with the Arrow variant was also unexpected. Beforehand, the continuous content of the Scroll variant seemed to be the most susceptible for this kind of error. Overshooting occurred almost exclusively in the second study on the stationary touchscreen (1 vs. 23 occurrences). Inspection of the video material of this part of the study strongly suggested that the effect might be a technical artefact, caused by a higher latency of the software on the stationary touchscreen than on the tablet. The touchscreen/software latency might also be the true cause for the effect of the display size on overshoots, but the rare overall occurrence of overshoots left the analysis of the video material inconclusive. Given the uncertain validity of the data concerning the Arrow variant, the low frequency, and the high variance, overshoots is not taken into account as a metric to identify the most suitable interaction concept for critical task environments.

While error rate is generally the most important metric for critical task environments, it is not as decisive for this experiment as it is for the list scrolling experiment. Since the experiment design only allowed for correctable errors, the consequences of errors were less severe. Errors in a navigation task will usually only worsen efficiency, satisfaction, and learnability, but will not compromise safety in most cases. Safe Home and Tabs showed the lowest error rate, which can be explained with their low motoric requirement and the lack of touch gestures. Page-Flip and Pinch–Spread both require touch gestures and had the highest error rate. Arrows and Scroll cannot be clearly assigned to either group due to their high variance. Since errors in this experiment could be made several times per task and did not hinder successful task completion, expressing them as a percentage may lead to misinterpretation. Nevertheless, if one considers that participants had to fulfil eight navigation tasks per variant (with an average distance between start and target screen of three), error rates were similar to the list scrolling study (1.5%–9.2%), but none of the variants reached below 1%. For critical task environments, this is rather high, but barely acceptable, given this concerns only correctable navigation errors.

An interference with the widgets on screen could have been another source of error. Especially the variants that use the part of the screen where the content is displayed for direct manipulation are prone to unwanted interaction with the widgets there when navigating to other content. In this study, this was expected for Page-Flip, Scroll, and Pinch–Spread. It was only observed with the Scroll variant. Five participants unwillingly interacted with the drag & drop task 13 times in total. None of these interactions led to a successful activation of the widget, which would pose a serious safety risk in a work environment. Nevertheless, the general potential for such errors makes Scroll less suitable for critical task environments than the alternatives.

When considering the hypotheses of the experiment, it can be concluded that for horizontal content change direct manipulation may lead to slower input speed and to more errors (depending on the concept; this experiment was only able to proof this for Page-Flip and Pinch–Spread, not Scroll). Overshooting seems to be of little importance for the usability of horizontal content change. Several variants that structure the content as pages are superior to Scroll, which presents the content continuously. However, it remains unclear if this is due to presentation of the content or the fact that Scroll uses direct manipulation.

Given the possibility to correct navigation errors, efficiency might be seen as the most important goal of a navigation concept in a critical task environment. For this reason, Tabs and Arrows seem most suitable for those use cases. The third-fastest interaction concept, Page-Flip, was already 44% slower than Tabs in the experiment. Given that the Tabs concept also does not allow overshooting and has the lowest error rate (together with Safe Home), it is the best choice for critical task environments. Since it does not use direct manipulation or animation, it is unlikely that an alternative is needed for use cases with limited hardware capability or gloves. The Arrows concept is possibly an equally fast and error-free alternative, but given the uncertain validity of the overshooting data, this cannot be said for sure.

The objective usability measures already lead to a distinct recommendation for this use case. Moreover, the Tabs variant is also in the leading group of concepts in user rating (usability questionnaire and AttrakDiff). Like the list scrolling experiment, this study also showed a clear dependency of user rating on input speed; overshooting and errors seem to be irrelevant. However, the distinction between the best-rated variants is not as clear as in the list scrolling study. Although Page-Flip and Scroll were 44% and 75% slower than Tabs, respectively, they were rated equally positive.

This could suggest that direct manipulation concepts are in fact rated more favorably than tap-based concepts, compensating some of their lower efficiency. This would be in accordance with the list scrolling results. Despite this, the slow Safe Home and Pinch–Spread were consistently rated lower than the other variants. For Pinch–Spread, the complexity of the touch gesture might be an additional reason. In conclusion, classic tap-based interaction concepts like Tabs can be very popular if they are suitable for the task.

Although this has been observed for smaller screens (Raptis, Tselios, Kjeldskov, & Skov), there seems to be no impact of display size on the observed metrics, at least not for the range between 8.9" and 21.5". The fact that there are no differences between tablet and stationary touchscreen seems plausible because the mode of interaction with the dominant hand is not different, as confirmed by analyzing the video material. More differences are likely to be seen between smaller display sizes where posture and usage of fingers tend to differ more (Popova-Dlugosch et al., 2014).

8 Practical Implications

8.1 Recommendations based on the Results

The results of the studies show the general relevance of the research questions. Unquestioned adoption of user interface concepts from consumer electronics can have a considerable impact on efficiency and error rate of operators. It is therefore important for practitioners to have recommendations and guidelines to inform their decisions for touchscreen user interface design in critical task environments.

The results also show that the influencing factors on total task time and error rate cannot be reduced to simple groups like tap-based vs. gesture-based, with virtual physics vs. without virtual physics. The influences are manifold and probably beyond the scope of a quantitative model or even a simple rule set. Therefore, recommendations should be based on realistic interaction concepts. General rules that forbid or allow interaction paradigms like drag and drop will not be helpful for practitioners to create ergonomic solutions.

If one looks at all the experiments described in this thesis, there are modern gesture-based touchscreen interaction concepts that work well in each of them. Touch gestures and virtual physics are well thought-out and working alternatives to conservative tap-based touchscreen interaction, even in critical task environments. Nevertheless, they have to be implemented carefully and be suitable for the intended task. However, they do not always present the most ergonomic solution, especially for critical task environments. That touch gestures can lead to worse efficiency and error rate compared to tap-based concepts could be reliably observed in both the list scrolling and the content change experiment. The differences between the experiments also show that it strongly depends on the use case if certain design decisions are beneficial, e.g. paged content instead of continuous content and the use of virtual inertia. Given their impact on crucial usability metrics, they are important factors that have to be considered in the design process of human–machine systems for critical tasks.

There are several means to ensure that users will not activate safety-critical functions unintentionally. A slider with virtual gravitation (“Slide to unlock”) remains the most suitable choice, as it offers good safety against unintentional activation, while needing little space and offering fast input speed, acceptable feedforward, and learnability.

For this use case, the advent of virtual physics is an improvement over preceding solutions. As long as there are hardware buttons for emergency shutdown, touchscreens seem a reasonable choice of input device even for many critical tasks. Given their limited capabilities for feedback and input precision, there will always be tasks that are better addressed with hardware input devices (e.g. buttons, joystick). Ensuring that safety-critical functions can only be activated with a special widget like the gravitation slider is a major premise for the use of touchscreens in critical task environments. Since many of the recommended interaction concepts have error rates higher than 1%, they should only be used for tasks that allow errors to be corrected.

While the observations of different variants of menus, function selectors, and numerical input methods failed to prove a clear advantage in efficiency or error rate of some concepts over others, they all showed that there are modern gesture-based alternatives to classic tap-based concepts that are rated equal or better by users. The error rates in these experiments were rather low. While experiments with more power to detect differences between the variants could likely be devised, there seems to be little need for that. Given the typical frequency of use of such touchscreen interaction concepts even in professional use cases, their impact on overall efficiency and safety is probably negligible. Variants with good feedforward and feedback are still to be preferred ensuring ease of learning and little potential of misunderstandings. Given how little differences between variants are, familiarity should also be preferred for the same reasons. For menus, a variant cascading from bottom up (Tree) can be a good alternative to the established cascading menu, addressing the occlusion problem. Function selectors profit mainly from their feedforward, showing the available options. A tab bar is a fast and safe function selector; adding touch gestures (Static Horizontal Selector) gives users another input option without worsening performance or safety. For numerical input, the number pad remains the preferred fast and safe choice. A gesture-controlled digit manipulator or digit manipulator wheel might be an alternative for some use cases.

For list scrolling, the recommended interaction concept for critical task environments is also the quasi-standard in consumer electronic devices: A directly manipulated list with virtual physics and an index bar. If touch gestures are not possible on the available hardware, buttons are equally insusceptible to errors, but considerably slower. If list length is predictably short, a variant without index bar or the buttons variant should be preferred.

For horizontal content change, the recommended interaction concept for critical task environments is tabs at the bottom of the screen. This is already a very common implementation in many industrial and healthcare use cases. Using a gesture-based concept where views can be swiped additionally seems acceptable, but not reasonable because input speed and error rate will be higher.

The fact that touch gestures and virtual physics can be advantageous is clearly shown by the good performance and error rates of concepts like direct manipulation scrolling or page-flip content change. However, touch gesture control will not always lead to better usability, as performance and rating of pinch–spread content switching clearly show.

The use of pagination can have different effects depending on the use case. While it is beneficial for horizontal content change, it did not fulfil the promise of lower error rate during list scrolling. Using multi-touch gestures in use cases that can be reasonably addressed with single-finger touch concepts can be harmful to input speed and error rate. At least for horizontal content change, this was shown by the poor performance of the pinch–spread concept.

8.2 Assessment of Validity and Practicality

Although the study was conducted in a laboratory environment with fictitious tasks and random participants, the results are deemed generally applicable to touchscreen in critical task environments, unless special parameters of the environment exist besides risk and time budget. Such factors can be vibrations, need to wear gloves, or dirt (see 5.1.2).

The differences in total task time and error rate between variants in the experiments range from 20% to 100%. The time the user interacts with the touchscreen system is often only a small fraction of the whole process the user takes part in, though. Therefore, even differences of 100% can be irrelevant to the economic viability of the whole process if larger influence factors vary strongly. On the other hand, even small differences in error rate can be critical and have strong effects on complex processes, if errors have severe consequences. However, if errors are easily correctable (e.g. navigation), they mainly influence efficiency, again with little relevance to complex processes with little touchscreen interaction. Nevertheless, error rate and efficiency also influence the ease of learning and satisfaction of the users, respectively, which can have long-lasting effects on overall efficiency and turnover rate. Efficiency and error rate of touchscreen interaction have relevant impact on the overall process in many use cases (e.g. healthcare, assembly-line work). The results and recommendations of this research can noticeably improve such environments.

A relevant difference between the study and realistic working conditions is the used touchscreen technology. While the experiments were conducted with state-of-the-art capacitive touchscreens, many critical task environments still use resistive touchscreens because they used to be cheaper, do not need glass surfaces (prone to breaking) and used to be the only possibility for input with gloves. This difference is becoming smaller because the price gap decreases and modern capacitive touchscreens also allow input with some kinds of gloves. They are also more resistant to impact due to harder glasses and allow for good encapsulation and ease of cleaning. Nevertheless, there is a difference because some resistive touchscreens tend to give in when pressed and have different frictional characteristics. Therefore, there is some justified doubt that all finding of this research are applicable to older resistive touchscreens. However, the majority of environments this research is aimed at is or will be equipped with modern technology that is well represented by the study design.

A problem of university research is the homogeneity of many samples. While it was avoided in these studies to have a majority of students as participants, the age distribution of the sample for the study concerning horizontal content change on a stationary touchscreen was not representative of the working population. The fact that the display size, which correlated with age in the sample, did not affect the observed metrics in the horizontal content change study suggests that the age distribution was not a problem.

Observed overshoots and error rates were rather low in all described studies. The resulting high variance might have concealed some of the effects. For future research, comparable studies should consist of longer or more frequent tasks to increase the number of interactions that can lead to errors. This would yield a study design more sensible to overshoots and errors and might reveal hitherto unknown effects. The relevance of these effects for practical application is doubtful, though. Given the number of influence factors that shape the design of a human–machine interface in a business environment, it is unlikely that very small differences in (correctable) errors will affect decisions dictated by available technology, ease of implementation, operating costs, or other factors.

Since all studied variants are based on already existing touchscreen interaction concepts, there is no barrier for easy implementation of the given recommendations in real-world use cases. Unfortunately, some industries rely heavily on certain software frameworks (e.g. Siemens WinCC in production or process engineering) that, depending on version, limit the possibilities in user interface design. That is why design recommendations for critical task environments should always include conservative interaction concepts as well. Since gesture-based touchscreen interaction has been state of the art for some time now, this problem will disappear as companies upgrade to newer software frameworks.

8.3 Publication of the Results

To improve the ergonomic quality of user interfaces in real-world applications it is paramount that scientific research and its findings are accessible and known to practitioners. Otherwise, there will be little improvement of existing solutions and the dangers of uninformed user interface design prevail (see 1 and 4.2).

The findings of this research as well as broader ergonomic recommendations were incorporated in new versions of the standard VDI/VDE 3850 “Development of Usable User Interfaces for Technical Plants”. As mentioned in 4.1.3, it did not address modern touchscreen technology in its previous version. This was changed in all three parts: “Concepts, Principles and Fundamental Recommendations” (VDI/VDE 3850-1), “Interaction Devices for Screens” (VDI/VDE 3850-2), and “Features, Design and Applications of User Interfaces with Touchscreens” (VDI/VDE 3850-3).

Apart from a paper concerning the list scrolling experiment (Breuninger, Popova-Dlugosch, & Bengler, 2013), a first overview over this research (Breuninger, Popova-Dlugosch, Pantförder, & Mayer, 2013) and a design guideline (Breuninger & Popova-Dlugosch, 2013) were published in 2013. Practical applications of this research were mentioned by Mayer and Pantförder (2014). The risks and challenges as well as general recommendations for touchscreen user interface design in technical plants based on this research were published by Breuninger and Popova-Dlugosch (2016). General recommendations on touchscreen interaction design were also incorporated into publications on ergonomic product design (Bubb, Popova-Dlugosch, & Breuninger, 2016) and ergonomic car design (Bubb, Bengler, Grünen, & Vollrath, 2015).

9 Summary and Outlook

In this thesis, the state of the art in touchscreen interaction design was described. The idiosyncrasies of touchscreen interactions were highlighted and explained with regard to ergonomic requirements. Special needs and challenges for application in critical task environments were identified. For this, the criticality of tasks was defined and known industry standards, guidelines, and research that addresses problems relevant to critical task environments was summarized. Based on the state of research and the current ergonomic challenges for touchscreen interaction in critical task environments, hypotheses were devised that required further research to improve recommendations for ergonomic touchscreen user interface design. The high-level findings of six experiments were presented, as well as a more detailed analysis of list scrolling and horizontal content switch, which show the most interesting results. They were conducted to study the influence of gesture-based direct manipulation and virtual physics on task time and error rate. The results of these studies show that gesture-based direct manipulation and virtual physics can have both positive and negative effects on task time and error rate. The validity of the results is considered acceptable. A directly manipulable list with virtual physics and an alphabetic index bar, as it is used in many modern consumer electronics, is recommended for list scrolling in critical task environments. For horizontal content change, tabs on the bottom of the screen are recommended. Sources aimed at practitioners, where insights from this research have been published, have been mentioned.

A general rejection of modern touchscreen interaction in critical task environments seems unjustified given the results of this research. However, a reasonable skepticism against free adoption of user interface concepts from consumer electronics is appropriate because the use of touch gestures and virtual physics may affect efficiency and error rate negatively. The drawbacks of touchscreen systems and their consequences in real-world applications, as described in 3.2 and 4.4, make touchscreens unsuitable for many use cases with high requirements of safety and efficiency. Serious accidents have happened that were partly credited to the choice of touchscreens over alternative user interfaces, such as the collision of the John S McCain with a tanker in 2017, which led to the death of ten people (National Transportation Safety Board, 2019). This has led to plans to replace touchscreens with hardware controls on U.S. Navy ships (Liptak, 2019). Therefore, to achieve an ergonomic design of the human–machine interface a wholesome usability engineering process is still paramount to assure safety and efficiency. This includes the unbiased analysis for the best choice of input technology and software design. Touchscreens and touch gestures should be considered reasonable options in this analysis. However, they are not the only options. A thorough empirical validation of the human–machine interface is the only reliable way to ensure a safe and efficient solution for critical task environments. This becomes even more relevant, the more the use case differs from common office or consumer electronics use cases.

For future research, similar studies should be conducted for other use cases, e.g. two-dimensional navigation (maps). Other related questions are described in 6.3: Errors caused by the interference of interaction concepts is a worthwhile research topic for critical task environments. In addition, the usability problem of lacking feedforward should be scrutinized more deeply because it is one of the major ergonomic problems of direct manipulation concepts. While it may have little impact on task time and error rate for experienced users, it impedes ease of learning and it should be tackled to utilize the full potential of touchscreen interaction.

Glossary

Affordance	The sum of the information an object or a software system offers to a user that suggests how the user might be able to interact with it. (Compare Feedforward)
Continuous content	A way of displaying content in a software system when there is more content than fits on screen. The user can choose how much content to move on screen continuously while moving other content off screen. (Compare Paged content)
Critical task	A task whose execution process and result may have severe impact on the safety of living beings or the economic viability of an enterprise
Direct manipulation (DM)	Controlling a software system by interacting with virtual objects instead of a command line. Also: Experiment variants that can be manipulated directly on the object/pane without dedicated widgets (see immediate interaction)
Double tap	Two taps with the fingertip on the same spot in quick succession (usually 500 ms or less)
Duration-based interaction concept	An interaction with a software system whose result is dependent on the duration of and delay between its steps. E.g. a double tap or a longpress
Feedback	The sum of the information a system gives to its users as a result of their actions. (Compare Feedforward)
Feedforward	The sum of the information an object or software systems offers to a user to show how the user can interact with it. (Compare Affordance, Feedback)
Immediate interaction	The quality of an interactive system that feed-

	forward, user input and feedback take place in close proximity
Longpress	A continuous contact of the fingertip at the same spot on a touchscreen that lasts between 500 ms and 1500 ms
M	Arithmetic mean; average
Moving objects, push background	A way of scrolling or moving virtual objects in a software system that simulates grabbing an object or plane that moves with the finger/stylus. (Compare Moving views)
Moving views, push viewport	A way of scrolling in a software system that simulates moving the viewport over an object or plane with dedicated controls (like scrollbar, mouse wheel, cursor keys). (Compare Moving objects)
Multi-touch	Interacting with a touchscreen with more than one finger simultaneously
Paged content	A way of displaying content in a software system when there is more content than fits on screen. The user can only change the amount of on-screen content in defined quantities, usually the amount that fits on screen or the page of a document. (Compare Continuous content)
Relief metaphor	A way of designing software systems to offer good feedforward and feedback. Buttons are displayed with virtual shadows to show their height, which decreases when they are pressed. Text boxes have inward shadows to appear recessed. Objects that can be dragged show drop shadows as if they hover over the background pane. Non-interactive objects are flat.
Semantic touch gesture	A touch gesture that does not manipulate a virtual object on screen directly, but mimics an action or object relevant to its function, e.g. spread-

	ing all fingers for "open"
SD	Standard deviation; a measure of the amount of variation in a data set
Swipe	Moving a finger on a touchscreen in one direction with continuous contact
Symbolic touch gesture	A form of semantic touch gesture that forms a symbol related to its function, e.g. a question mark for help
TA-EG	Technikaffinität – Elektronische Geräte (technical affinity – electronic devices); a questionnaire to assess how someone feels about electronic devices
Tap	A short contact of the fingertip with the screen at one spot, usually less than 500 ms
Touch gesture	Moving at least one finger on a touchscreen with continuous contact
Touchscreen	An input and output device that can recognize and locate touch of fingers or pointing devices like styluses on the surface of its screen
Usability	A technical system's effectiveness, efficiency and satisfaction with which specified users achieve specified goals in particular environments
User Experience (UX)	A subjective quality of a product or service that can be influenced by its usability, visual aesthetics, elegance, modernity, effect on social status, perceived quality, joy of use, and other factors
Widget	An interactive element in a software, e.g. a button or a scrollbar
WIMP	Windows, Icons, Menus, Pointer. An interaction paradigm that represents programs and media as icons and shows them in freely movable windows that can be controlled with menus using a pointer symbol

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Appendix A: Statistical Analysis

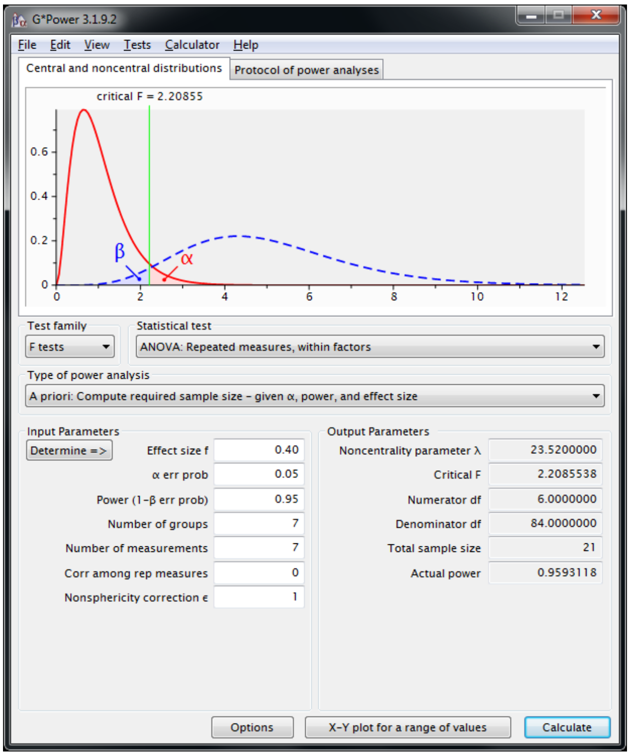

Figure 80: A Priori Calculation: Horizontal Content Change

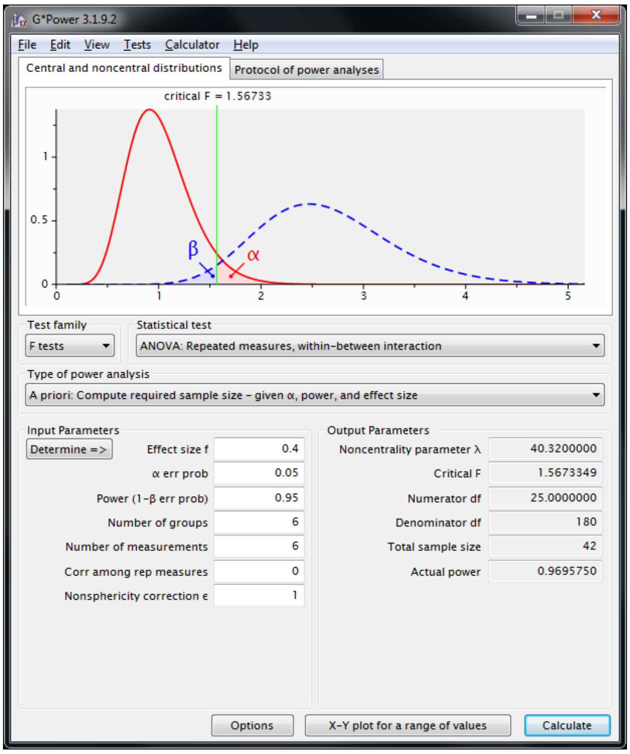

Figure 81: A Priori Calculation: List Scrolling

General Linear Model (List Scrolling, Total Task Time)

Within-Subjects Factors

Measure: MEASURE_1

variant	list_length	Dependent Variable
1	1	buttons_short
	2	buttons_medium
	3	buttons_long
2	1	scrollbar_short
	2	scrollbar_medium
	3	scrollbar_long
3	1	pagedm_short
	2	pagedm_medium
	3	pagedm_long
4	1	dmwphy_short
	2	dmwphy_medium
	3	dmwphy_long
5	1	dmnophy_short
	2	dmnophy_medium
	3	dmnophy_long
6	1	dmwphyABC_short
	2	dmwphyABC_medium
	3	dmwphyABC_long
7	1	dmnophyABC_short
	2	dmnophyABC_medium
	3	dmnophyABC_long

Descriptive Statistics

	Mean	Std. Deviation	N
buttons_short	41912,3125	9648,49808	32
buttons_medium	63291,9375	13510,84166	32
buttons_long	109358,6563	27175,87308	32
scrollbar_short	49985,5625	15122,36420	32
scrollbar_medium	64266,6875	20182,55721	32
scrollbar_long	97973,3438	20936,04372	32
pagedm_short	43649,6563	11139,72931	32
pagedm_medium	67840,7813	11772,66766	32
pagedm_long	144613,8438	30245,57868	32
dmwphy_short	41289,5938	9684,98027	32
dmwphy_medium	61255,8438	16747,05153	32
dmwphy_long	108445,5625	20575,68384	32

dmnophy_short	43104,0937	11129,64983	32
dmnophy_medium	65342,7500	11741,55250	32
dmnophy_long	129727,7500	27011,03145	32
dmwphyABC_short	45178,5313	11699,16963	32
dmwphyABC_medium	46675,2500	10100,14012	32
dmwphyABC_long	66437,0000	19465,86925	32
dmnophyABC_short	46586,6875	12362,19715	32
dmnophyABC_medium	48228,4063	10940,00623	32
dmnophyABC_long	60572,2188	14498,80557	32

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.
variant	Pillai's Trace	,941	69,277[b]	6,000	26,000	,000
	Wilks' Lambda	,059	69,277[b]	6,000	26,000	,000
	Hotelling's Trace	15,987	69,277[b]	6,000	26,000	,000
	Roy's Largest Root	15,987	69,277[b]	6,000	26,000	,000
list_length	Pillai's Trace	,963	394,117[b]	2,000	30,000	,000
	Wilks' Lambda	,037	394,117[b]	2,000	30,000	,000
	Hotelling's Trace	26,274	394,117[b]	2,000	30,000	,000
	Roy's Largest Root	26,274	394,117[b]	2,000	30,000	,000
variant * list_length	Pillai's Trace	,971	54,868[b]	12,000	20,000	,000
	Wilks' Lambda	,029	54,868[b]	12,000	20,000	,000
	Hotelling's Trace	32,921	54,868[b]	12,000	20,000	,000
	Roy's Largest Root	32,921	54,868[b]	12,000	20,000	,000

a. Design: Intercept

Within Subjects Design: variant + list_length + variant * list_length

b. Exact statistic

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
variant	,351	30,133	20	,069	,722	,854	,167
list_length	,251	41,450	2	,000	,572	,579	,500
variant * list_length	,001	188,931	77	,000	,395	,475	,083

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept

Within Subjects Design: variant + list_length + variant * list_length

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
variant	Sphericity Assumed	90863511224,437	6	15143918537,406	91,244	,000
	Greenhouse-Geisser	90863511224,437	4,330	20982334219,850	91,244	,000
	Huynh-Feldt	90863511224,437	5,121	17743232364,358	91,244	,000
	Lower-bound	90863511224,437	1,000	90863511224,437	91,244	,000
Error(variant)	Sphericity Assumed	30870657133,467	186	165971274,911		
	Greenhouse-Geisser	30870657133,467	134,245	229957969,760		
	Huynh-Feldt	30870657133,467	158,752	194458712,207		
	Lower-bound	30870657133,467	31,000	995827649,467		
list_length	Sphericity Assumed	404676669113,152	2	202338334556,576	750,852	,000
	Greenhouse-Geisser	404676669113,152	1,144	353856871749,966	750,852	,000
	Huynh-Feldt	404676669113,152	1,159	349239020585,011	750,852	,000
	Lower-bound	404676669113,152	1,000	404676669113,152	750,852	,000
Error(list_length)	Sphericity Assumed	16707656398,086	62	269478329,001		
	Greenhouse-Geisser	16707656398,086	35,452	471273813,308		
	Huynh-Feldt	16707656398,086	35,921	465123664,755		
	Lower-bound	16707656398,086	31,000	538956658,003		
variant * list_length	Sphericity Assumed	106455870223,098	12	8871322518,592	77,606	,000
	Greenhouse-Geisser	106455870223,098	4,743	22444296503,294	77,606	,000
	Huynh-Feldt	106455870223,098	5,704	18662076391,226	77,606	,000
	Lower-bound	106455870223,098	1,000	106455870223,098	77,606	,000
Error(variant*list_length)	Sphericity Assumed	42524021554,997	372	114311885,901		
	Greenhouse-Geisser	42524021554,997	147,037	289207145,341		
	Huynh-Feldt	42524021554,997	176,836	240471152,146		
	Lower-bound	42524021554,997	31,000	1371742630,806		

Tests of Within-Subjects Contrasts

Measure: MEASURE_1

Source	variant	list_length	Type III Sum of Squares	df	Mean Square	F	Sig.
variant	Level 2 vs. Level 1		19424105,681	1	19424105,681	,257	,616
	Level 3 vs. Level 1		6135771864,500	1	6135771864,500	76,559	,000
	Level 4 vs. Level 1		45363606,253	1	45363606,253	,489	,490

	Level 5 vs. Level 1		1982264130,125	1	1982264130,125	13,546	,001
	Level 6 vs. Level 1		11258851740,500	1	11258851740,500	98,383	,000
	Level 7 vs. Level 1		12450669851,254	1	12450669851,254	128,105	,000
Error(variant)	Level 2 vs. Level 1		2344130274,764	31	75617105,638		
	Level 3 vs. Level 1		2484475328,611	31	80144365,439		
	Level 4 vs. Level 1		2874731703,191	31	92733280,748		
	Level 5 vs. Level 1		4536241838,986	31	146330381,903		
	Level 6 vs. Level 1		3547607227,500	31	114438942,823		
	Level 7 vs. Level 1		3012927437,302	31	97191207,655		
list_length		Level 1 vs. Level 3	107341679938,778	1	107341679938,778	813,830	,000
		Level 2 vs. Level 3	58864380507,031	1	58864380507,031	715,837	,000
Error(list_length)		Level 1 vs. Level 3	4088804747,630	31	131896927,343		
		Level 2 vs. Level 3	2549179459,357	31	82231595,463		
variant * list_length	Level 2 vs. Level 1	Level 1 vs. Level 3	12116340946,125	1	12116340946,125	21,432	,000
		Level 2 vs. Level 3	4888676640,125	1	4888676640,125	7,808	,009
	Level 3 vs. Level 1	Level 1 vs. Level 3	35950267188,781	1	35950267188,781	72,678	,000
		Level 2 vs. Level 3	30172145487,781	1	30172145487,781	50,389	,000
	Level 4 vs. Level 1	Level 1 vs. Level 3	2698164,500	1	2698164,500	,009	,925
		Level 2 vs. Level 3	40356128,000	1	40356128,000	,085	,773
	Level 5 vs. Level 1	Level 1 vs. Level 3	11768618071,125	1	11768618071,125	22,319	,000
		Level 2 vs. Level 3	10737901694,531	1	10737901694,531	15,624	,000

	Level 6 vs. Level 1	Level 1 vs. Level 3	68266233504,500	1	68266233504,500	88,909	,000
		Level 2 vs. Level 3	22142444190,031	1	22142444190,031	40,122	,000
	Level 7 vs. Level 1	Level 1 vs. Level 3	91457871141,125	1	91457871141,125	214,639	,000
		Level 2 vs. Level 3	36391500990,281	1	36391500990,281	124,187	,000
Error(variant*list_length)	Level 2 vs. Level 1	Level 1 vs. Level 3	17525445219,875	31	565336942,577		
		Level 2 vs. Level 3	19409842531,875	31	626123952,641		
	Level 3 vs. Level 1	Level 1 vs. Level 3	15334146494,219	31	494649886,910		
		Level 2 vs. Level 3	18562367789,219	31	598786057,717		
	Level 4 vs. Level 1	Level 1 vs. Level 3	9215808061,500	31	297284131,016		
		Level 2 vs. Level 3	14716466202,000	31	474724716,194		
	Level 5 vs. Level 1	Level 1 vs. Level 3	16346193624,875	31	527296568,544		
		Level 2 vs. Level 3	21305041770,469	31	687259411,951		
	Level 6 vs. Level 1	Level 1 vs. Level 3	23802349385,500	31	767817722,113		
		Level 2 vs. Level 3	17108229878,969	31	551878383,193		
	Level 7 vs. Level 1	Level 1 vs. Level 3	13209109504,875	31	426100306,609		
		Level 2 vs. Level 3	9084170116,719	31	293037745,701		

Tests of Between-Subjects Effects

Measure: MEASURE_1

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	151666498835,281	1	151666498835,281	980,319	,000
Error	4796051404,136	31	154711335,617		

Estimated Marginal Means

1. variant

Estimates

Measure: MEASURE_1

variant	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	71520,969	2762,959	65885,876	77156,061
2	70741,865	2948,550	64728,257	76755,473
3	85368,094	2640,763	79982,223	90753,965
4	70330,333	2498,498	65234,614	75426,053
5	79391,531	2538,738	74213,741	84569,322
6	52763,594	2026,433	48630,656	56896,532
7	51795,771	2029,945	47655,672	55935,870

Pairwise Comparisons

Measure: MEASURE_1

(I) variant	(J) variant	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	95% Confidence Interval for Difference[b] Upper Bound
1	2	779,104	1537,216	1,000	-4307,305	5865,513
	3	-13847,125*	1582,565	,000	-19083,584	-8610,666
	4	1190,635	1702,326	1,000	-4442,096	6823,367
	5	-7870,562*	2138,416	,018	-14946,247	-794,878
	6	18757,375*	1891,089	,000	12500,058	25014,692
	7	19725,198*	1742,764	,000	13958,666	25491,730
2	1	-779,104	1537,216	1,000	-5865,513	4307,305
	3	-14626,229*	1823,323	,000	-20659,320	-8593,138
	4	411,531	1822,291	1,000	-5618,146	6441,208
	5	-8649,667*	2594,880	,047	-17235,718	-63,616
	6	17978,271*	2318,411	,000	10307,012	25649,530
	7	18946,094*	1851,963	,000	12818,238	25073,949
3	1	13847,125*	1582,565	,000	8610,666	19083,584
	2	14626,229*	1823,323	,000	8593,138	20659,320
	4	15037,760*	1756,062	,000	9227,228	20848,293
	5	5976,563*	1637,686	,020	557,717	11395,408
	6	32604,500*	1901,150	,000	26313,892	38895,108
	7	33572,323*	1603,872	,000	28265,361	38879,284
4	1	-1190,635	1702,326	1,000	-6823,367	4442,096
	2	-411,531	1822,291	1,000	-6441,208	5618,146

	3	-15037,760*	1756,062	,000	-20848,293	-9227,228
	5	-9061,198*	2038,119	,002	-15805,016	-2317,380
	6	17566,740*	1780,388	,000	11675,716	23457,763
	7	18534,563*	1642,460	,000	13099,919	23969,206
5	1	7870,562*	2138,416	,018	794,878	14946,247
	2	8649,667*	2594,880	,047	63,616	17235,718
	3	-5976,563*	1637,686	,020	-11395,408	-557,717
	4	9061,198*	2038,119	,002	2317,380	15805,016
	6	26627,938*	1974,574	,000	20094,380	33161,495
	7	27595,760*	1863,701	,000	21429,067	33762,454
6	1	-18757,375*	1891,089	,000	-25014,692	-12500,058
	2	-17978,271*	2318,411	,000	-25649,530	-10307,012
	3	-32604,500*	1901,150	,000	-38895,108	-26313,892
	4	-17566,740*	1780,388	,000	-23457,763	-11675,716
	5	-26627,938*	1974,574	,000	-33161,495	-20094,380
	7	967,823	1459,795	1,000	-3862,410	5798,056
7	1	-19725,198*	1742,764	,000	-25491,730	-13958,666
	2	-18946,094*	1851,963	,000	-25073,949	-12818,238
	3	-33572,323*	1603,872	,000	-38879,284	-28265,361
	4	-18534,563*	1642,460	,000	-23969,206	-13099,919
	5	-27595,760*	1863,701	,000	-33762,454	-21429,067
	6	-967,823	1459,795	1,000	-5798,056	3862,410

Based on estimated marginal means

*. The mean difference is significant at the ,05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	,941	69,277[a]	6,000	26,000	,000
Wilks' lambda	,059	69,277[a]	6,000	26,000	,000
Hotelling's trace	15,987	69,277[a]	6,000	26,000	,000
Roy's largest root	15,987	69,277[a]	6,000	26,000	,000

Each F tests the multivariate effect of variant. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a. Exact statistic

2. list_length

Estimates

Measure: MEASURE_1

list_length	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	44529,491	1657,065	41149,885	47909,097
2	59557,379	1933,601	55613,774	63500,985
3	102446,911	3228,865	95861,598	109032,224

Pairwise Comparisons

Measure: MEASURE_1

(I) list_length	(J) list_length	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	-15027,888*	725,709	,000	-16864,603	-13191,173
	3	-57917,420*	2030,216	,000	-63055,747	-52779,092
2	1	15027,888*	725,709	,000	13191,173	16864,603
	3	-42889,531*	1603,040	,000	-46946,707	-38832,356
3	1	57917,420*	2030,216	,000	52779,092	63055,747
	2	42889,531*	1603,040	,000	38832,356	46946,707

Based on estimated marginal means

*. The mean difference is significant at the ,05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	,963	394,117[a]	2,000	30,000	,000
Wilks' lambda	,037	394,117[a]	2,000	30,000	,000
Hotelling's trace	26,274	394,117[a]	2,000	30,000	,000
Roy's largest root	26,274	394,117[a]	2,000	30,000	,000

Each F tests the multivariate effect of list_length. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a. Exact statistic

3. variant * list_length

Measure: MEASURE_1

variant	list_length	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
1	1	41912,313	1705,630	38433,658	45390,967
	2	63291,938	2388,402	58420,760	68163,115
	3	109358,656	4804,061	99560,709	119156,603
2	1	49985,563	2673,282	44533,369	55437,756
	2	64266,688	3567,806	56990,100	71543,275
	3	97973,344	3701,005	90425,095	105521,592
3	1	43649,656	1969,245	39633,356	47665,957
	2	67840,781	2081,133	63596,282	72085,281
	3	144613,844	5346,713	133709,150	155518,538
4	1	41289,594	1712,079	37797,786	44781,401
	2	61255,844	2960,488	55217,888	67293,800
	3	108445,563	3637,301	101027,237	115863,888
5	1	43104,094	1967,463	39091,427	47116,760
	2	65342,750	2075,633	61109,469	69576,031
	3	129727,750	4774,921	119989,235	139466,265
6	1	45178,531	2068,141	40960,531	49396,532
	2	46675,250	1785,469	43033,761	50316,739
	3	66437,000	3441,112	59418,806	73455,194
7	1	46586,688	2185,348	42129,640	51043,735
	2	48228,406	1933,938	44284,113	52172,699
	3	60572,219	2563,051	55344,842	65799,596

General Linear Model (List Scrolling, Overshoots)

Within-Subjects Factors

Measure: MEASURE_1

variant	list_length	Dependent Variable
1	1	buttons_short
	2	buttons_medium
	3	buttons_long
2	1	scrollbar_short
	2	scrollbar_medium
	3	scrollbar_long

3	1	pagedm_short
	2	pagedm_medium
	3	pagedm_long
4	1	dmwphy_short
	2	dmwphy_medium
	3	dmwphy_long
5	1	dmnophy_short
	2	dmnophy_medium
	3	dmnophy_long
6	1	dmwphyABC_short
	2	dmwphyABC_medium
	3	dmwphyABC_long
7	1	dmnophyABC_short
	2	dmnophyABC_medium
	3	dmnophyABC_long

Descriptive Statistics

	Mean	Std. Deviation	N
buttons_short	,0625	,24593	32
buttons_medium	2,3125	1,65466	32
buttons_long	4,4375	1,84806	32
scrollbar_short	,0938	,29614	32
scrollbar_medium	1,9375	1,84806	32
scrollbar_long	6,0000	1,86651	32
pagedm_short	,4062	,55992	32
pagedm_medium	1,2813	1,08462	32
pagedm_long	3,0625	1,41279	32
dmwphy_short	,1250	,33601	32
dmwphy_medium	1,9063	1,59352	32
dmwphy_long	3,9063	1,48887	32
dmnophy_short	,0625	,24593	32
dmnophy_medium	,7500	,91581	32
dmnophy_long	1,4062	1,26642	32
dmwphyABC_short	,3438	,54532	32
dmwphyABC_medium	1,8125	,85901	32
dmwphyABC_long	1,2813	,99139	32
dmnophyABC_short	,0938	,29614	32
dmnophyABC_medium	1,7500	,95038	32
dmnophyABC_long	1,5625	1,10534	32

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.
variant	Pillai's Trace	,901	39,558[b]	6,000	26,000	,000
	Wilks' Lambda	,099	39,558[b]	6,000	26,000	,000
	Hotelling's Trace	9,129	39,558[b]	6,000	26,000	,000
	Roy's Largest Root	9,129	39,558[b]	6,000	26,000	,000
list_length	Pillai's Trace	,939	231,818[b]	2,000	30,000	,000
	Wilks' Lambda	,061	231,818[b]	2,000	30,000	,000
	Hotelling's Trace	15,455	231,818[b]	2,000	30,000	,000
	Roy's Largest Root	15,455	231,818[b]	2,000	30,000	,000
variant * list_length	Pillai's Trace	,940	25,975[b]	12,000	20,000	,000
	Wilks' Lambda	,060	25,975[b]	12,000	20,000	,000
	Hotelling's Trace	15,585	25,975[b]	12,000	20,000	,000
	Roy's Largest Root	15,585	25,975[b]	12,000	20,000	,000

a. Design: Intercept

Within Subjects Design: variant + list_length + variant * list_length

b. Exact statistic

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
variant	,433	24,090	20	,241	,790	,950	,167
list_length	,947	1,631	2	,442	,950	1,000	,500
variant * list_length	,017	108,818	77	,012	,632	,856	,083

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept

Within Subjects Design: variant + list_length + variant * list_length

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
variant	Sphericity Assumed	278,488	6	46,415	32,283	,000
	Greenhouse-Geisser	278,488	4,738	58,778	32,283	,000
	Huynh-Feldt	278,488	5,697	48,883	32,283	,000
	Lower-bound	278,488	1,000	278,488	32,283	,000

Error(variant)	Sphericity Assumed	267,417	186	1,438		
	Greenhouse-Geisser	267,417	146,878	1,821		
	Huynh-Feldt	267,417	176,608	1,514		
	Lower-bound	267,417	31,000	8,626		
list_length	Sphericity Assumed	957,973	2	478,987	293,538	,000
	Greenhouse-Geisser	957,973	1,899	504,338	293,538	,000
	Huynh-Feldt	957,973	2,000	478,987	293,538	,000
	Lower-bound	957,973	1,000	957,973	293,538	,000
Error(list_length)	Sphericity Assumed	101,170	62	1,632		
	Greenhouse-Geisser	101,170	58,884	1,718		
	Huynh-Feldt	101,170	62,000	1,632		
	Lower-bound	101,170	31,000	3,264		
variant * list_length	Sphericity Assumed	395,985	12	32,999	32,515	,000
	Greenhouse-Geisser	395,985	7,582	52,227	32,515	,000
	Huynh-Feldt	395,985	10,275	38,538	32,515	,000
	Lower-bound	395,985	1,000	395,985	32,515	,000
Error(variant*list_length)	Sphericity Assumed	377,539	372	1,015		
	Greenhouse-Geisser	377,539	235,043	1,606		
	Huynh-Feldt	377,539	318,532	1,185		
	Lower-bound	377,539	31,000	12,179		

Tests of Within-Subjects Contrasts

Measure: MEASURE_1

Source	variant	list_length	Type III Sum of Squares	df	Mean Square	F	Sig.
variant	Level 2 vs. Level 1		5,281	1	5,281	3,353	,077
	Level 3 vs. Level 1		15,125	1	15,125	19,019	,000
	Level 4 vs. Level 1		2,722	1	2,722	2,660	,113
	Level 5 vs. Level 1		75,031	1	75,031	100,779	,000
	Level 6 vs. Level 1		40,500	1	40,500	39,031	,000
	Level 7 vs. Level 1		41,253	1	41,253	42,359	,000

Error(variant)	Level 2 vs. Level 1		48,830	31	1,575		
	Level 3 vs. Level 1		24,653	31	,795		
	Level 4 vs. Level 1		31,722	31	1,023		
	Level 5 vs. Level 1		23,080	31	,745		
	Level 6 vs. Level 1		32,167	31	1,038		
	Level 7 vs. Level 1		30,191	31	,974		
list_length		Level 2 vs. Level 1	72,860	1	72,860	168,742	,000
		Level 3 vs. Level 1	273,613	1	273,613	478,840	,000
Error(list_length)		Level 2 vs. Level 1	13,385	31	,432		
		Level 3 vs. Level 1	17,714	31	,571		
variant * list_length	Level 2 vs. Level 1	Level 2 vs. Level 1	5,281	1	5,281	,932	,342
		Level 3 vs. Level 1	75,031	1	75,031	15,107	,000
	Level 3 vs. Level 1	Level 2 vs. Level 1	60,500	1	60,500	16,821	,000
		Level 3 vs. Level 1	94,531	1	94,531	29,168	,000
	Level 4 vs. Level 1	Level 2 vs. Level 1	7,031	1	7,031	1,703	,201
		Level 3 vs. Level 1	11,281	1	11,281	2,468	,126
	Level 5 vs. Level 1	Level 2 vs. Level 1	78,125	1	78,125	22,875	,000
		Level 3 vs. Level 1	294,031	1	294,031	77,927	,000
	Level 6 vs. Level 1	Level 2 vs. Level 1	19,531	1	19,531	6,767	,014
		Level 3 vs. Level 1	378,125	1	378,125	78,211	,000
	Level 7 vs. Level 1	Level 2 vs. Level 1	11,281	1	11,281	5,321	,028

		Level 3 vs. Level 1	270,281	1	270,281	65,093	,000
Error(variant*list_length)	Level 2 vs. Level 1	Level 2 vs. Level 1	175,719	31	5,668		
		Level 3 vs. Level 1	153,969	31	4,967		
	Level 3 vs. Level 1	Level 2 vs. Level 1	111,500	31	3,597		
		Level 3 vs. Level 1	100,469	31	3,241		
	Level 4 vs. Level 1	Level 2 vs. Level 1	127,969	31	4,128		
		Level 3 vs. Level 1	141,719	31	4,572		
	Level 5 vs. Level 1	Level 2 vs. Level 1	105,875	31	3,415		
		Level 3 vs. Level 1	116,969	31	3,773		
	Level 6 vs. Level 1	Level 2 vs. Level 1	89,469	31	2,886		
		Level 3 vs. Level 1	149,875	31	4,835		
	Level 7 vs. Level 1	Level 2 vs. Level 1	65,719	31	2,120		
		Level 3 vs. Level 1	128,719	31	4,152		

Tests of Between-Subjects Effects

Measure: MEASURE_1

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	86,837	1	86,837	432,051	,000
Error	6,231	31	,201		

Estimated Marginal Means

1. variant

Estimates

Measure: MEASURE_1

variant	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	2,271	,172	1,920	2,622
2	2,677	,183	2,304	3,050
3	1,583	,126	1,326	1,841
4	1,979	,141	1,691	2,267
5	,740	,107	,522	,957
6	1,146	,104	,934	1,357
7	1,135	,113	,905	1,366

Pairwise Comparisons

Measure: MEASURE_1

(I) variant	(J) variant	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	-,406	,222	1,000	-1,140	,328
	3	,687*	,158	,003	,166	1,209
	4	,292	,179	1,000	-,300	,883
	5	1,531*	,153	,000	1,027	2,036
	6	1,125*	,180	,000	,529	1,721
	7	1,135*	,174	,000	,558	1,713
2	1	,406	,222	1,000	-,328	1,140
	3	1,094*	,207	,000	,409	1,779
	4	,698*	,209	,045	,007	1,388
	5	1,938*	,172	,000	1,370	2,505
	6	1,531*	,211	,000	,835	2,228
	7	1,542*	,175	,000	,963	2,121
3	1	-,687*	,158	,003	-1,209	-,166
	2	-1,094*	,207	,000	-1,779	-,409
	4	-,396	,138	,151	-,851	,059
	5	,844*	,137	,000	,390	1,298
	6	,438	,147	,118	-,049	,924
	7	,448	,187	,475	-,170	1,066

4	1	-,292	,179	1,000	-,883	,300
	2	-,698*	,209	,045	-1,388	-,007
	3	,396	,138	,151	-,059	,851
	5	1,240*	,151	,000	,741	1,738
	6	,833*	,173	,001	,260	1,407
	7	,844*	,173	,001	,273	1,415
5	1	-1,531*	,153	,000	-2,036	-1,027
	2	-1,938*	,172	,000	-2,505	-1,370
	3	-,844*	,137	,000	-1,298	-,390
	4	-1,240*	,151	,000	-1,738	-,741
	6	-,406	,149	,224	-,901	,088
	7	-,396	,152	,297	-,900	,108
6	1	-1,125*	,180	,000	-1,721	-,529
	2	-1,531*	,211	,000	-2,228	-,835
	3	-,438	,147	,118	-,924	,049
	4	-,833*	,173	,001	-1,407	-,260
	5	,406	,149	,224	-,088	,901
	7	,010	,154	1,000	-,501	,521
7	1	-1,135*	,174	,000	-1,713	-,558
	2	-1,542*	,175	,000	-2,121	-,963
	3	-,448	,187	,475	-1,066	,170
	4	-,844*	,173	,001	-1,415	-,273
	5	,396	,152	,297	-,108	,900
	6	-,010	,154	1,000	-,521	,501

Based on estimated marginal means

*. The mean difference is significant at the ,05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	,901	39,558[a]	6,000	26,000	,000
Wilks' lambda	,099	39,558[a]	6,000	26,000	,000
Hotelling's trace	9,129	39,558[a]	6,000	26,000	,000
Roy's largest root	9,129	39,558[a]	6,000	26,000	,000

Each F tests the multivariate effect of variant. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a. Exact statistic

2. list_length

Estimates

Measure: MEASURE_1

list_length	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	,170	,024	,122	,218
2	1,679	,119	1,437	1,921
3	3,094	,137	2,814	3,373

Pairwise Comparisons

Measure: MEASURE_1

(I) list_length	(J) list_length	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	-1,509*	,116	,000	-1,803	-1,215
	3	-2,924*	,134	,000	-3,262	-2,586
2	1	1,509*	,116	,000	1,215	1,803
	3	-1,415*	,111	,000	-1,697	-1,134
3	1	2,924*	,134	,000	2,586	3,262
	2	1,415*	,111	,000	1,134	1,697

Based on estimated marginal means

*. The mean difference is significant at the ,05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	,939	231,818[a]	2,000	30,000	,000
Wilks' lambda	,061	231,818[a]	2,000	30,000	,000
Hotelling's trace	15,455	231,818[a]	2,000	30,000	,000
Roy's largest root	15,455	231,818[a]	2,000	30,000	,000

Each F tests the multivariate effect of list_length. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a. Exact statistic

3. variant * list_length

Measure: MEASURE_1

variant	list_length	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
1	1	,063	,043	-,026	,151
	2	2,313	,293	1,716	2,909
	3	4,438	,327	3,771	5,104
2	1	,094	,052	-,013	,201
	2	1,938	,327	1,271	2,604
	3	6,000	,330	5,327	6,673
3	1	,406	,099	,204	,608
	2	1,281	,192	,890	1,672
	3	3,063	,250	2,553	3,572
4	1	,125	,059	,004	,246
	2	1,906	,282	1,332	2,481
	3	3,906	,263	3,369	4,443
5	1	,063	,043	-,026	,151
	2	,750	,162	,420	1,080
	3	1,406	,224	,950	1,863
6	1	,344	,096	,147	,540
	2	1,813	,152	1,503	2,122
	3	1,281	,175	,924	1,639
7	1	,094	,052	-,013	,201
	2	1,750	,168	1,407	2,093
	3	1,563	,195	1,164	1,961

General Linear Model (List Scrolling, Errors)

Within-Subjects Factors

Measure: MEASURE_1

variant	list_length	Dependent Variable
1	1	buttons_short
	2	buttons_medium
	3	buttons_long
2	1	scrollbar_short
	2	scrollbar_medium
	3	scrollbar_long
3	1	pagedm_short
	2	pagedm_medium
	3	pagedm_long

4	1	dmwphy_short
	2	dmwphy_medium
	3	dmwphy_long
5	1	dmnophy_short
	2	dmnophy_medium
	3	dmnophy_long
6	1	dmwphyABC_short
	2	dmwphyABC_medium
	3	dmwphyABC_long
7	1	dmnophyABC_short
	2	dmnophyABC_medium
	3	dmnophyABC_long

Descriptive Statistics

	Mean	Std. Deviation	N
buttons_short	,0000	,00000	32
buttons_medium	,0938	,29614	32
buttons_long	,0625	,24593	32
scrollbar_short	,0313	,17678	32
scrollbar_medium	,0313	,17678	32
scrollbar_long	,0000	,00000	32
pagedm_short	,1250	,33601	32
pagedm_medium	,1875	,39656	32
pagedm_long	,7500	,95038	32
dmwphy_short	,0313	,17678	32
dmwphy_medium	,2188	,49084	32
dmwphy_long	,3750	,79312	32
dmnophy_short	,2500	,50800	32
dmnophy_medium	,2500	,50800	32
dmnophy_long	1,0000	1,13592	32
dmwphyABC_short	,0938	,29614	32
dmwphyABC_medium	,0625	,24593	32
dmwphyABC_long	,0625	,24593	32
dmnophyABC_short	,0000	,00000	32
dmnophyABC_medium	,0313	,17678	32
dmnophyABC_long	,3125	,59229	32

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.
variant	Pillai's Trace	,630	7,387[b]	6,000	26,000	,000
	Wilks' Lambda	,370	7,387[b]	6,000	26,000	,000
	Hotelling's Trace	1,705	7,387[b]	6,000	26,000	,000
	Roy's Largest Root	1,705	7,387[b]	6,000	26,000	,000
list_length	Pillai's Trace	,473	13,476[b]	2,000	30,000	,000
	Wilks' Lambda	,527	13,476[b]	2,000	30,000	,000
	Hotelling's Trace	,898	13,476[b]	2,000	30,000	,000
	Roy's Largest Root	,898	13,476[b]	2,000	30,000	,000
variant * list_length	Pillai's Trace	,636	2,907[b]	12,000	20,000	,017
	Wilks' Lambda	,364	2,907[b]	12,000	20,000	,017
	Hotelling's Trace	1,744	2,907[b]	12,000	20,000	,017
	Roy's Largest Root	1,744	2,907[b]	12,000	20,000	,017

a. Design: Intercept

Within Subjects Design: variant + list_length + variant * list_length

b. Exact statistic

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
variant	,022	109,564	20	,000	,483	,539	,167
list_length	,573	16,699	2	,000	,701	,724	,500
variant * list_length	,000	255,179	77	,000	,424	,517	,083

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept

Within Subjects Design: variant + list_length + variant * list_length

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
variant	Sphericity Assumed	18,280	6	3,047	13,900	,000
	Greenhouse-Geisser	18,280	2,900	6,303	13,900	,000
	Huynh-Feldt	18,280	3,232	5,657	13,900	,000
	Lower-bound	18,280	1,000	18,280	13,900	,001

Error(variant)	Sphericity Assumed	40,768	186	,219		
	Greenhouse-Geisser	40,768	89,908	,453		
	Huynh-Feldt	40,768	100,181	,407		
	Lower-bound	40,768	31,000	1,315		
list_length	Sphericity Assumed	10,807	2	5,403	22,049	,000
	Greenhouse-Geisser	10,807	1,402	7,710	22,049	,000
	Huynh-Feldt	10,807	1,448	7,464	22,049	,000
	Lower-bound	10,807	1,000	10,807	22,049	,000
Error(list_length)	Sphericity Assumed	15,193	62	,245		
	Greenhouse-Geisser	15,193	43,452	,350		
	Huynh-Feldt	15,193	44,883	,339		
	Lower-bound	15,193	31,000	,490		
variant * list_length	Sphericity Assumed	12,756	12	1,063	5,075	,000
	Greenhouse-Geisser	12,756	5,085	2,508	5,075	,000
	Huynh-Feldt	12,756	6,202	2,057	5,075	,000
	Lower-bound	12,756	1,000	12,756	5,075	,031
Error(variant*list_length)	Sphericity Assumed	77,911	372	,209		
	Greenhouse-Geisser	77,911	157,642	,494		
	Huynh-Feldt	77,911	192,267	,405		
	Lower-bound	77,911	31,000	2,513		

Tests of Within-Subjects Contrasts

Measure: MEASURE_1

Source	variant	list_length	Type III Sum of Squares	df	Mean Square	F	Sig.
variant	Level 2 vs. Level 1		,031	1	,031	1,848	,184
	Level 3 vs. Level 1		2,920	1	2,920	22,188	,000
	Level 4 vs. Level 1		,781	1	,781	6,417	,017
	Level 5 vs. Level 1		6,420	1	6,420	22,054	,000
	Level 6 vs. Level 1		,014	1	,014	,392	,536
	Level 7 vs. Level 1		,125	1	,125	2,709	,110

Error(variant)	Level 2 vs. Level 1		,524	31	,017		
	Level 3 vs. Level 1		4,080	31	,132		
	Level 4 vs. Level 1		3,774	31	,122		
	Level 5 vs. Level 1		9,024	31	,291		
	Level 6 vs. Level 1		1,097	31	,035		
	Level 7 vs. Level 1		1,431	31	,046		
list_length		Level 1 vs. Level 3	2,695	1	2,695	27,849	,000
		Level 2 vs. Level 3	1,860	1	1,860	20,944	,000
Error(list_length)		Level 1 vs. Level 3	2,999	31	,097		
		Level 2 vs. Level 3	2,753	31	,089		
variant * list_length	Level 2 vs. Level 1	Level 1 vs. Level 3	,281	1	,281	3,207	,083
		Level 2 vs. Level 3	,000	1	,000	,000	1,000
	Level 3 vs. Level 1	Level 1 vs. Level 3	10,125	1	10,125	8,287	,007
		Level 2 vs. Level 3	11,281	1	11,281	8,383	,007
	Level 4 vs. Level 1	Level 1 vs. Level 3	2,531	1	2,531	3,207	,083
		Level 2 vs. Level 3	1,125	1	1,125	1,130	,296
	Level 5 vs. Level 1	Level 1 vs. Level 3	15,125	1	15,125	9,216	,005
		Level 2 vs. Level 3	19,531	1	19,531	14,601	,001
	Level 6 vs. Level 1	Level 1 vs. Level 3	,281	1	,281	1,298	,263
		Level 2 vs. Level 3	,031	1	,031	,139	,712
	Level 7 vs. Level 1	Level 1 vs. Level 3	2,000	1	2,000	4,429	,044

		Level 2 vs. Level 3	3,125	1	3,125	4,235	,048
Error(variant*list_length)	Level 2 vs. Level 1	Level 1 vs. Level 3	2,719	31	,088		
		Level 2 vs. Level 3	6,000	31	,194		
	Level 3 vs. Level 1	Level 1 vs. Level 3	37,875	31	1,222		
		Level 2 vs. Level 3	41,719	31	1,346		
	Level 4 vs. Level 1	Level 1 vs. Level 3	24,469	31	,789		
		Level 2 vs. Level 3	30,875	31	,996		
	Level 5 vs. Level 1	Level 1 vs. Level 3	50,875	31	1,641		
		Level 2 vs. Level 3	41,469	31	1,338		
	Level 6 vs. Level 1	Level 1 vs. Level 3	6,719	31	,217		
		Level 2 vs. Level 3	6,969	31	,225		
	Level 7 vs. Level 1	Level 1 vs. Level 3	14,000	31	,452		
		Level 2 vs. Level 3	22,875	31	,738		

Tests of Between-Subjects Effects

Measure: MEASURE_1

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	1,143	1	1,143	65,937	,000
Error	,537	31	,017		

Estimated Marginal Means

1. variant

Estimates

Measure: MEASURE_1

variant	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	,052	,022	,008	,096
2	,021	,014	-,009	,050
3	,354	,060	,232	,476
4	,208	,053	,099	,317
5	,500	,091	,314	,686
6	,073	,029	,014	,132
7	,115	,035	,042	,187

Pairwise Comparisons

Measure: MEASURE_1

(I) variant	(J) variant	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	,031	,023	1,000	-,045	,107
	3	-,302*	,064	,001	-,514	-,090
	4	-,156	,062	,348	-,360	,048
	5	-,448*	,095	,001	-,764	-,132
	6	-,021	,033	1,000	-,131	,089
	7	-,062	,038	1,000	-,188	,063
2	1	-,031	,023	1,000	-,107	,045
	3	-,333*	,062	,000	-,538	-,129
	4	-,188*	,056	,044	-,372	-,003
	5	-,479*	,092	,000	-,784	-,174
	6	-,052	,026	1,000	-,139	,035
	7	-,094	,037	,369	-,217	,030
3	1	,302*	,064	,001	,090	,514
	2	,333*	,062	,000	,129	,538
	4	,146	,086	1,000	-,138	,430
	5	-,146	,081	1,000	-,412	,121
	6	,281*	,069	,006	,054	,509
	7	,240*	,072	,048	,001	,478

4	1	,156	,062	,348	-,048	,360
	2	,188*	,056	,044	,003	,372
	3	-,146	,086	1,000	-,430	,138
	5	-,292	,089	,057	-,588	,004
	6	,135	,063	,845	-,074	,345
	7	,094	,058	1,000	-,100	,287
5	1	,448*	,095	,001	,132	,764
	2	,479*	,092	,000	,174	,784
	3	,146	,081	1,000	-,121	,412
	4	,292	,089	,057	-,004	,588
	6	,427*	,097	,003	,105	,749
	7	,385*	,087	,002	,096	,675
6	1	,021	,033	1,000	-,089	,131
	2	,052	,026	1,000	-,035	,139
	3	-,281*	,069	,006	-,509	-,054
	4	-,135	,063	,845	-,345	,074
	5	-,427*	,097	,003	-,749	-,105
	7	-,042	,044	1,000	-,188	,105
7	1	,062	,038	1,000	-,063	,188
	2	,094	,037	,369	-,030	,217
	3	-,240*	,072	,048	-,478	-,001
	4	-,094	,058	1,000	-,287	,100
	5	-,385*	,087	,002	-,675	-,096
	6	,042	,044	1,000	-,105	,188

Based on estimated marginal means

*. The mean difference is significant at the ,05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	,630	7,387[a]	6,000	26,000	,000
Wilks' lambda	,370	7,387[a]	6,000	26,000	,000
Hotelling's trace	1,705	7,387[a]	6,000	26,000	,000
Roy's largest root	1,705	7,387[a]	6,000	26,000	,000

Each F tests the multivariate effect of variant. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a. Exact statistic

2. list_length

Estimates

Measure: MEASURE_1

list_length	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	,076	,020	,035	,117
2	,125	,020	,084	,166
3	,366	,055	,254	,478

Pairwise Comparisons

Measure: MEASURE_1

(I) list_length	(J) list_length	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	95% Confidence Interval for Difference[b] Upper Bound
1	2	-,049	,028	,257	-,119	,021
	3	-,290*	,055	,000	-,429	-,151
2	1	,049	,028	,257	-,021	,119
	3	-,241*	,053	,000	-,374	-,108
3	1	,290*	,055	,000	,151	,429
	2	,241*	,053	,000	,108	,374

Based on estimated marginal means

*. The mean difference is significant at the ,05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	,473	13,476[a]	2,000	30,000	,000
Wilks' lambda	,527	13,476[a]	2,000	30,000	,000
Hotelling's trace	,898	13,476[a]	2,000	30,000	,000
Roy's largest root	,898	13,476[a]	2,000	30,000	,000

Each F tests the multivariate effect of list_length. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a. Exact statistic

3. variant * list_length

Measure: MEASURE_1

variant	list_length	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
1	1	,000	,000	,000	,000
	2	,094	,052	-,013	,201
	3	,063	,043	-,026	,151
2	1	,031	,031	-,032	,095
	2	,031	,031	-,032	,095
	3	,000	,000	,000	,000
3	1	,125	,059	,004	,246
	2	,188	,070	,045	,330
	3	,750	,168	,407	1,093
4	1	,031	,031	-,032	,095
	2	,219	,087	,042	,396
	3	,375	,140	,089	,661
5	1	,250	,090	,067	,433
	2	,250	,090	,067	,433
	3	1,000	,201	,590	1,410
6	1	,094	,052	-,013	,201
	2	,063	,043	-,026	,151
	3	,063	,043	-,026	,151
7	1	,000	,000	,000	,000
	2	,031	,031	-,032	,095
	3	,313	,105	,099	,526

General Linear Model (Content Change, Total Task Time)

Within-Subjects Factors

Measure: totaltasktime

variants	Dependent Variable
1	safehome
2	tabs
3	arrows
4	pageflip
5	scroll
6	pinchspread

Between-Subjects Factors

		Value Label	N
display size	0	klein	30
	1	groß	30

Descriptive Statistics

	display size	Mean	Std. Deviation	N
safe home	klein	17,35880	10,283571	30
	groß	19,65443	6,625956	30
	Total	18,50662	8,654428	60
tabs	klein	9,62537	6,938326	30
	groß	8,48403	3,049992	30
	Total	9,05470	5,344697	60
arrows	klein	11,40393	12,018035	30
	groß	7,84050	3,002459	30
	Total	9,62222	8,868590	60
page-flip	klein	11,78153	10,650303	30
	groß	14,41833	6,417453	30
	Total	13,09993	8,818373	60
scroll	klein	15,04180	11,381651	30
	groß	16,70770	10,429532	30
	Total	15,87475	10,855620	60
pinch–spread	klein	26,61857	14,424439	30
	groß	29,91147	10,865799	30
	Total	28,26502	12,769415	60

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.
variants	Pillai's Trace	,831	53,162[b]	5,000	54,000	,000
	Wilks' Lambda	,169	53,162[b]	5,000	54,000	,000
	Hotelling's Trace	4,922	53,162[b]	5,000	54,000	,000
	Roy's Largest Root	4,922	53,162[b]	5,000	54,000	,000
variants * display_size	Pillai's Trace	,224	3,123[b]	5,000	54,000	,015
	Wilks' Lambda	,776	3,123[b]	5,000	54,000	,015
	Hotelling's Trace	,289	3,123[b]	5,000	54,000	,015
	Roy's Largest Root	,289	3,123[b]	5,000	54,000	,015

a. Design: Intercept + display_size

Within Subjects Design: variants

b. Exact statistic

Mauchly's Test of Sphericity[a]

Measure: totaltasktime

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
variants	,347	59,400	14	,000	,668	,726	,200

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + display_size
Within Subjects Design: variants

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: totaltasktime

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
variants	Sphericity Assumed	15218,327	5	3043,665	53,169	,000
	Greenhouse-Geisser	15218,327	3,342	4553,774	53,169	,000
	Huynh-Feldt	15218,327	3,632	4190,137	53,169	,000
	Lower-bound	15218,327	1,000	15218,327	53,169	,000
variants * display_size	Sphericity Assumed	530,378	5	106,076	1,853	,103
	Greenhouse-Geisser	530,378	3,342	158,705	1,853	,132
	Huynh-Feldt	530,378	3,632	146,032	1,853	,127
	Lower-bound	530,378	1,000	530,378	1,853	,179
Error(variants)	Sphericity Assumed	16601,183	290	57,245		
	Greenhouse-Geisser	16601,183	193,831	85,648		
	Huynh-Feldt	16601,183	210,653	78,808		
	Lower-bound	16601,183	58,000	286,227		

Tests of Within-Subjects Contrasts

Measure: totaltasktime

Source	variants	Type III Sum of Squares	df	Mean Square	F	Sig.
variants	Linear	4533,972	1	4533,972	64,336	,000
	Quadratic	9952,478	1	9952,478	223,277	,000
	Cubic	55,120	1	55,120	,946	,335
	Order 4	650,830	1	650,830	15,615	,000
	Order 5	25,928	1	25,928	,364	,549

variants * display_size	Linear	82,389	1	82,389	1,169	,284
	Quadratic	172,990	1	172,990	3,881	,054
	Cubic	129,792	1	129,792	2,227	,141
	Order 4	2,503	1	2,503	,060	,807
	Order 5	142,703	1	142,703	2,004	,162
Error(variants)	Linear	4087,463	58	70,474		
	Quadratic	2585,323	58	44,575		
	Cubic	3380,764	58	58,289		
	Order 4	2417,381	58	41,679		
	Order 5	4130,251	58	71,211		

Tests of Between-Subjects Effects

Measure: totaltasktime

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	89157,470	1	89157,470	351,601	,000
display_size	67,249	1	67,249	,265	,609
Error	14707,383	58	253,576		

Estimated Marginal Means

1. display size

Estimates

Measure: totaltasktime

display size	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
klein	15,305	1,187	12,929	17,681
groß	16,169	1,187	13,794	18,545

Pairwise Comparisons

Measure: totaltasktime

(I) display size	(J) display size	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
klein	groß	-,864	1,679	,609	-4,224	2,496
groß	klein	,864	1,679	,609	-2,496	4,224

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.

Univariate Tests

Measure: totaltasktime

	Sum of Squares	df	Mean Square	F	Sig.
Contrast	11,208	1	11,208	,265	,609
Error	2451,230	58	42,263		

The F tests the effect of display size. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

2. variants

Estimates

Measure: totaltasktime

variants	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	18,507	1,117	16,271	20,742
2	9,055	,692	7,670	10,440
3	9,622	1,131	7,359	11,886
4	13,100	1,135	10,828	15,372
5	15,875	1,409	13,054	18,696
6	28,265	1,649	24,965	31,565

Pairwise Comparisons

Measure: totaltasktime

(I) variants	(J) variants	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	95% Confidence Interval for Difference[b] Upper Bound
1	2	9,452*	1,119	,000	6,027	12,877
	3	8,884*	,885	,000	6,175	11,594
	4	5,407*	1,352	,003	1,268	9,546
	5	2,632	1,017	,183	-,481	5,745
	6	-9,758*	1,722	,000	-15,031	-4,486
2	1	-9,452*	1,119	,000	-12,877	-6,027
	3	-,568	1,181	1,000	-4,184	3,049
	4	-4,045*	1,183	,017	-7,668	-,422
	5	-6,820*	1,434	,000	-11,212	-2,428
	6	-19,210*	1,581	,000	-24,051	-14,369
3	1	-8,884*	,885	,000	-11,594	-6,175
	2	,568	1,181	1,000	-3,049	4,184
	4	-3,478	1,282	,131	-7,402	,446
	5	-6,253*	1,082	,000	-9,566	-2,939
	6	-18,643*	1,688	,000	-23,811	-13,475

4	1	-5,407*	1,352	,003	-9,546	-1,268
	2	4,045*	1,183	,017	,422	7,668
	3	3,478	1,282	,131	-,446	7,402
	5	-2,775	1,508	1,000	-7,392	1,842
	6	-15,165*	1,399	,000	-19,449	-10,881
5	1	-2,632	1,017	,183	-5,745	,481
	2	6,820*	1,434	,000	2,428	11,212
	3	6,253*	1,082	,000	2,939	9,566
	4	2,775	1,508	1,000	-1,842	7,392
	6	-12,390*	1,874	,000	-18,129	-6,651
6	1	9,758*	1,722	,000	4,486	15,031
	2	19,210*	1,581	,000	14,369	24,051
	3	18,643*	1,688	,000	13,475	23,811
	4	15,165*	1,399	,000	10,881	19,449
	5	12,390*	1,874	,000	6,651	18,129

Based on estimated marginal means

*. The mean difference is significant at the ,05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	,831	53,162[a]	5,000	54,000	,000
Wilks' lambda	,169	53,162[a]	5,000	54,000	,000
Hotelling's trace	4,922	53,162[a]	5,000	54,000	,000
Roy's largest root	4,922	53,162[a]	5,000	54,000	,000

Each F tests the multivariate effect of variants. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a. Exact statistic

3. display size * variants

Measure: totaltasktime

				95% Confidence Interval	
display size	variants	Mean	Std. Error	Lower Bound	Upper Bound
klein	1	17,359	1,579	14,197	20,520
	2	9,625	,978	7,667	11,584
	3	11,404	1,599	8,203	14,605
	4	11,782	1,605	8,568	14,995
	5	15,042	1,993	11,052	19,031
	6	26,619	2,331	21,952	31,285

groß	1	19,654	1,579	16,493	22,816
	2	8,484	,978	6,525	10,443
	3	7,841	1,599	4,639	11,042
	4	14,418	1,605	11,205	17,632
	5	16,708	1,993	12,718	20,697
	6	29,911	2,331	25,245	34,578

General Linear Model (Content Change, Overshoots)

Within-Subjects Factors

Measure: overshoots

variants	Dependent Variable
1	safehome
2	tabs
3	arrows
4	pageflip
5	scroll
6	pinchspread

Between-Subjects Factors

		Value Label	N
display_size	0	small	30
	1	large	30

Descriptive Statistics

	display_size	Mean	Std. Deviation	N
safehome	small	,00	,000	30
	large	,00	,000	30
	Total	,00	,000	60
tabs	small	,00	,000	30
	large	,00	,000	30
	Total	,00	,000	60
arrows	small	,03	,183	30
	large	,77	,504	30
	Total	,40	,527	60
pageflip	small	,00	,000	30
	large	,20	,407	30
	Total	,10	,303	60

scroll	small	,07	,254	30
	large	,27	,521	30
	Total	,17	,418	60
pinchspread	small	,13	,571	30
	large	,03	,183	30
	Total	,08	,424	60

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.
variants	Pillai's Trace	,592	19,976[b]	4,000	55,000	,000
	Wilks' Lambda	,408	19,976[b]	4,000	55,000	,000
	Hotelling's Trace	1,453	19,976[b]	4,000	55,000	,000
	Roy's Largest Root	1,453	19,976[b]	4,000	55,000	,000
variants * display_size	Pillai's Trace	,512	14,410[b]	4,000	55,000	,000
	Wilks' Lambda	,488	14,410[b]	4,000	55,000	,000
	Hotelling's Trace	1,048	14,410[b]	4,000	55,000	,000
	Roy's Largest Root	1,048	14,410[b]	4,000	55,000	,000

a. Design: Intercept + display_size

Within Subjects Design: variants

b. Exact statistic

Mauchly's Test of Sphericity[a]

Measure: overshoots

					Epsilon[b]		
Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Greenhouse-Geisser	Huynh-Feldt	Lower-bound
variants	,000	.	14	.	,638	,691	,200

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + display_size

Within Subjects Design: variants

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: overshoots

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
variants	Sphericity Assumed	6,658	5	1,332	14,080	,000
	Greenhouse-Geisser	6,658	3,191	2,087	14,080	,000
	Huynh-Feldt	6,658	3,456	1,926	14,080	,000
	Lower-bound	6,658	1,000	6,658	14,080	,000
variants * display_size	Sphericity Assumed	6,747	5	1,349	14,268	,000
	Greenhouse-Geisser	6,747	3,191	2,115	14,268	,000
	Huynh-Feldt	6,747	3,456	1,952	14,268	,000
	Lower-bound	6,747	1,000	6,747	14,268	,000
Error(variants)	Sphericity Assumed	27,428	290	,095		
	Greenhouse-Geisser	27,428	185,053	,148		
	Huynh-Feldt	27,428	200,461	,137		
	Lower-bound	27,428	58,000	,473		

Tests of Within-Subjects Contrasts

Measure: overshoots

Source	variants	Type III Sum of Squares	df	Mean Square	F	Sig.
variants	Linear	,326	1	,326	3,682	,060
	Quadratic	2,187	1	2,187	18,236	,000
	Cubic	,068	1	,068	,703	,405
	Order 4	,729	1	,729	8,101	,006
	Order 5	3,348	1	3,348	42,687	,000
variants * display_size	Linear	,040	1	,040	,455	,503
	Quadratic	3,510	1	3,510	29,258	,000
	Cubic	,005	1	,005	,047	,829
	Order 4	,729	1	,729	8,101	,006
	Order 5	2,464	1	2,464	31,408	,000
Error(variants)	Linear	5,134	58	,089		
	Quadratic	6,958	58	,120		
	Cubic	5,567	58	,096		
	Order 4	5,220	58	,090		
	Order 5	4,549	58	,078		

Tests of Between-Subjects Effects

Measure: overshoots

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	5,625	1	5,625	55,558	,000
display_size	2,669	1	2,669	26,366	,000
Error	5,872	58	,101		

Estimated Marginal Means

1. display_size

Estimates

Measure: overshoots

display_size	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
small	,039	,024	-,009	,086
large	,211	,024	,164	,259

Pairwise Comparisons

Measure: overshoots

(I) display_size	(J) display_size	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
small	large	-,172*	,034	,000	-,239	-,105
large	small	,172*	,034	,000	,105	,239

Based on estimated marginal means

*. The mean difference is significant at the ,05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Univariate Tests

Measure: overshoots

	Sum of Squares	df	Mean Square	F	Sig.
Contrast	,445	1	,445	26,366	,000
Error	,979	58	,017		

The F tests the effect of display_size. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

2. variants

Estimates

Measure: overshoots

variants	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	,000	,000	,000	,000
2	,000	,000	,000	,000
3	,400	,049	,302	,498
4	,100	,037	,026	,174
5	,167	,053	,061	,273
6	,083	,055	-,026	,193

Pairwise Comparisons

Measure: overshoots

(I) variants	(J) variants	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	,000	,000	.	,000	,000
	3	-,400*	,049	,000	-,550	-,250
	4	-,100	,037	,139	-,214	,014
	5	-,167*	,053	,039	-,329	-,005
	6	-,083	,055	1,000	-,251	,084
2	1	,000	,000	.	,000	,000
	3	-,400*	,049	,000	-,550	-,250
	4	-,100	,037	,139	-,214	,014
	5	-,167*	,053	,039	-,329	-,005
	6	-,083	,055	1,000	-,251	,084
3	1	,400*	,049	,000	,250	,550
	2	,400*	,049	,000	,250	,550
	4	,300*	,054	,000	,133	,467
	5	,233*	,073	,033	,010	,456
	6	,317*	,077	,002	,081	,552
4	1	,100	,037	,139	-,014	,214
	2	,100	,037	,139	-,014	,214
	3	-,300*	,054	,000	-,467	-,133
	5	-,067	,058	1,000	-,244	,111
	6	,017	,067	1,000	-,189	,222

5	1	,167*	,053	,039	,005	,329
	2	,167*	,053	,039	,005	,329
	3	-,233*	,073	,033	-,456	-,010
	4	,067	,058	1,000	-,111	,244
	6	,083	,078	1,000	-,156	,322
6	1	,083	,055	1,000	-,084	,251
	2	,083	,055	1,000	-,084	,251
	3	-,317*	,077	,002	-,552	-,081
	4	-,017	,067	1,000	-,222	,189
	5	-,083	,078	1,000	-,322	,156

Based on estimated marginal means

*. The mean difference is significant at the ,05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	,592	19,976[a]	4,000	55,000	,000
Wilks' lambda	,408	19,976[a]	4,000	55,000	,000
Hotelling's trace	1,453	19,976[a]	4,000	55,000	,000
Roy's largest root	1,453	19,976[a]	4,000	55,000	,000

Each F tests the multivariate effect of variants. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a. Exact statistic

3. display_size * variants

Measure: overshoots

				95% Confidence Interval	
display_size	variants	Mean	Std. Error	Lower Bound	Upper Bound
small	1	,000	,000	,000	,000
	2	,000	,000	,000	,000
	3	,033	,069	-,105	,172
	4	,000	,053	-,105	,105
	5	,067	,075	-,083	,216
	6	,133	,077	-,022	,288
large	1	,000	,000	,000	,000
	2	,000	,000	,000	,000
	3	,767	,069	,628	,905
	4	,200	,053	,095	,305
	5	,267	,075	,117	,416
	6	,033	,077	-,122	,188

General Linear Model (Content Change, Errors)

Within-Subjects Factors

Measure: errors

varianten	Dependent Variable
1	safehome
2	tabs
3	arrows
4	pageflip
5	scroll
6	pinchspread

Between-Subjects Factors

		Value Label	N
display size	0	small	30
	1	large	30

Descriptive Statistics

	display size	Mean	Std. Deviation	N
safe home	small	,13	,346	30
	large	,10	,305	30
	Total	,12	,324	60
tabs	small	,30	,535	30
	large	,17	,461	30
	Total	,23	,500	60
arrows	small	,27	,640	30
	large	,77	,504	30
	Total	,52	,624	60
page-flip	small	1,07	,254	30
	large	,40	,621	30
	Total	,73	,578	60
scroll	small	,73	2,753	30
	large	,50	,900	30
	Total	,62	2,034	60
pinch–spread	small	,23	,774	30
	large	1,13	1,042	30
	Total	,68	1,017	60

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.
varianten	Pillai's Trace	,548	13,089[b]	5,000	54,000	,000
	Wilks' Lambda	,452	13,089[b]	5,000	54,000	,000
	Hotelling's Trace	1,212	13,089[b]	5,000	54,000	,000
	Roy's Largest Root	1,212	13,089[b]	5,000	54,000	,000
varianten * display_size	Pillai's Trace	,601	16,258[b]	5,000	54,000	,000
	Wilks' Lambda	,399	16,258[b]	5,000	54,000	,000
	Hotelling's Trace	1,505	16,258[b]	5,000	54,000	,000
	Roy's Largest Root	1,505	16,258[b]	5,000	54,000	,000

a. Design: Intercept + display_size

Within Subjects Design: varianten

b. Exact statistic

Mauchly's Test of Sphericity[a]

Measure: errors

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
varianten	,019	221,308	14	,000	,360	,377	,200

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + display_size

Within Subjects Design: varianten

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: errors

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
varianten	Sphericity Assumed	19,100	5	3,820	3,954	,002
	Greenhouse-Geisser	19,100	1,801	10,607	3,954	,026
	Huynh-Feldt	19,100	1,887	10,122	3,954	,024
	Lower-bound	19,100	1,000	19,100	3,954	,051
varianten * display_size	Sphericity Assumed	23,389	5	4,678	4,842	,000
	Greenhouse-Geisser	23,389	1,801	12,989	4,842	,012
	Huynh-Feldt	23,389	1,887	12,395	4,842	,011
	Lower-bound	23,389	1,000	23,389	4,842	,032

Error(varianten)	Sphericity Assumed	280,178	290	,966		
	Greenhouse-Geisser	280,178	104,443	2,683		
	Huynh-Feldt	280,178	109,442	2,560		
	Lower-bound	280,178	58,000	4,831		

Tests of Within-Subjects Contrasts

Measure: errors

Source	varianten	Type III Sum of Squares	df	Mean Square	F	Sig.
varianten	Linear	15,120	1	15,120	17,519	,000
	Quadratic	2,445	1	2,445	5,135	,027
	Cubic	,171	1	,171	,147	,702
	Order 4	1,205	1	1,205	,887	,350
	Order 5	,159	1	,159	,163	,687
varianten * display_size	Linear	2,194	1	2,194	2,542	,116
	Quadratic	5,143	1	5,143	10,802	,002
	Cubic	8,389	1	8,389	7,226	,009
	Order 4	1,429	1	1,429	1,052	,309
	Order 5	6,233	1	6,233	6,417	,014
Error(varianten)	Linear	50,057	58	,863		
	Quadratic	27,615	58	,476		
	Cubic	67,334	58	1,161		
	Order 4	78,830	58	1,359		
	Order 5	56,342	58	,971		

Tests of Between-Subjects Effects

Measure: errors

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	84,100	1	84,100	75,094	,000
display_size	,278	1	,278	,248	,620
Error	64,956	58	1,120		

Estimated Marginal Means

1. display size

Estimates

Measure: errors

display size	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
small	,456	,079	,298	,613
large	,511	,079	,353	,669

Pairwise Comparisons

Measure: errors

(I) display size	(J) display size	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
small	large	-,056	,112	,620	-,279	,168
large	small	,056	,112	,620	-,168	,279

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.

Univariate Tests

Measure: errors

	Sum of Squares	df	Mean Square	F	Sig.
Contrast	,046	1	,046	,248	,620
Error	10,826	58	,187		

The F tests the effect of display size. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

2. varianten

Estimates

Measure: errors

varianten	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	,117	,042	,032	,201
2	,233	,064	,104	,362
3	,517	,074	,368	,665
4	,733	,061	,611	,856
5	,617	,264	,087	1,146
6	,683	,118	,446	,920

Pairwise Comparisons

Measure: errors

(I) varianten	(J) varianten	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
1	2	-,117	,076	1,000	-,349	,116
	3	-,400*	,080	,000	-,644	-,156
	4	-,617*	,080	,000	-,861	-,372
	5	-,500	,268	1,000	-1,321	,321
	6	-,567*	,133	,001	-,974	-,159
2	1	,117	,076	1,000	-,116	,349
	3	-,283	,107	,161	-,612	,046
	4	-,500*	,097	,000	-,797	-,203
	5	-,383	,270	1,000	-1,211	,444
	6	-,450*	,134	,021	-,861	-,039
3	1	,400*	,080	,000	,156	,644
	2	,283	,107	,161	-,046	,612
	4	-,217	,096	,406	-,509	,076
	5	-,100	,230	1,000	-,803	,603
	6	-,167	,150	1,000	-,625	,292
4	1	,617*	,080	,000	,372	,861
	2	,500*	,097	,000	,203	,797
	3	,217	,096	,406	-,076	,509
	5	,117	,274	1,000	-,722	,956
	6	,050	,122	1,000	-,324	,424
5	1	,500	,268	1,000	-,321	1,321
	2	,383	,270	1,000	-,444	1,211
	3	,100	,230	1,000	-,603	,803
	4	-,117	,274	1,000	-,956	,722
	6	-,067	,298	1,000	-,978	,845
6	1	,567*	,133	,001	,159	,974
	2	,450*	,134	,021	,039	,861
	3	,167	,150	1,000	-,292	,625
	4	-,050	,122	1,000	-,424	,324
	5	,067	,298	1,000	-,845	,978

Based on estimated marginal means

*. The mean difference is significant at the ,05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	,548	13,089[a]	5,000	54,000	,000
Wilks' lambda	,452	13,089[a]	5,000	54,000	,000
Hotelling's trace	1,212	13,089[a]	5,000	54,000	,000
Roy's largest root	1,212	13,089[a]	5,000	54,000	,000

Each F tests the multivariate effect of varianten. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a. Exact statistic

3. display size * varianten

Measure: errors

				95% Confidence Interval	
display size	varianten	Mean	Std. Error	Lower Bound	Upper Bound
small	1	,133	,060	,014	,252
	2	,300	,091	,117	,483
	3	,267	,105	,056	,477
	4	1,067	,087	,893	1,240
	5	,733	,374	-,015	1,482
	6	,233	,168	-,102	,569
large	1	,100	,060	-,019	,219
	2	,167	,091	-,016	,349
	3	,767	,105	,556	,977
	4	,400	,087	,227	,573
	5	,500	,374	-,249	1,249
	6	1,133	,168	,798	1,469

Appendix B: Questionnaires

Demographischer Teil

2 [D1]Alter *

Bitte geben Sie Ihre Antwort hier ein:

3 [D2]Geschlecht *

Bitte wählen Sie nur eine der folgenden Antworten aus:

- weiblich
- männlich

4 [D3]Sind Die Rechtshänder oder Linkshänder? *

Bitte wählen Sie nur eine der folgenden Antworten aus:

- Rechtshänder
- Linkshänder

5 [D4]Sichtigkeit *

Bitte wählen Sie **maximal** 3 Antworten aus:

- Normalsichtig
- Kurzsichtig
- Weitsichtig
- Farbsehschwäche/-blindheit

6 [D5]Tragen Sie normalerweise eine Sehhilfe? *

Beantworten Sie diese Frage nur, wenn folgende Bedingungen erfüllt sind:
° Die Antwort war bei Frage '5 [D4]' (Sichtigkeit)

Bitte wählen Sie nur eine der folgenden Antworten aus:

- Ja
- Nein

7 [D6]Welche der folgenden Geräte mit Touchscreen benutzen Sie privat oder beruflich? *

Bitte wählen Sie die zutreffende Antwort für jeden Punkt aus:

	nie	selten	gelegentlich	häufig	sehr häufig
Mobiltelefon					
Tablet					
Laptop/Notebook (mit Touchscreen)					
Navigationssystem (mit Touchscreen)					
Sonstige					

8 [D6s]Wenn sonstige Geräte verwendet werden, welche

Beantworten Sie diese Frage nur, wenn folgende Bedingungen erfüllt sind:
° Die Antwort war NICHT D7W1'nie' bei Frage '7 [D6]' (Welche der folgenden Geräte mit Touchscreen benutzen Sie privat oder beruflich? (Sonstige))

Bitte geben Sie Ihre Antwort hier ein:

Technikaffinität

9 [T1] *

Bitte wählen Sie die zutreffende Antwort für jeden Punkt aus:

	Trifft gar nicht zu	Trifft eher nicht zu	Teils/Teils	Trifft eher zu	Trifft völlig zu
Ich liebe es, neue elektronische Geräte zu besitzen	●	●	●	●	●
Elektronische Geräte machen krank	●	●	●	●	●
Ich gehe gerne in den Fachhandel für elektronische Geräte	●	●	●	●	●
Ich habe bzw. hätte Verständnisprobleme beim Lesen von Elektronik- und Computerzeitschriften	●	●	●	●	●
Elektronische Geräte ermöglichen einen hohen Lebensstandard	●	●	●	●	●
Elektronische Geräte führen zu geistiger Verarmung	●	●	●	●	●
Elektronische Geräte machen vieles umständlicher	●	●	●	●	●
Ich informiere mich über elektronische Geräte, auch wenn ich keine Kaufabsicht habe	●	●	●	●	●
Elektronische Geräte machen unabhängig	●	●	●	●	●
Es macht mir Spaß, elektronische Geräte auszuprobieren	●	●	●	●	●
Elektronische Geräte erleichtern mir den Alltag	●	●	●	●	●
Elektronische Geräte erhöhen die Sicherheit	●	●	●	●	●
Elektronische Geräte verringern den Kontakt zwischen Menschen	●	●	●	●	●
Ich kenne die meisten					

Funktionen der elektronischen Geräte, die ich besitze	●	●	●	●	●
Ich bin begeistert, wenn ein neues elektronisches Gerät auf den Markt kommt	●	●	●	●	●
Elektronische Geräte verursachen Stress	●	●	●	●	●
Ich kenne mich im Bereich elektronischer Geräte aus	●	●	●	●	●
Es fällt mir leicht, die Bedienung eines elektronischen Gerätes zu erlernen	●	●	●	●	●
Elektronische Geräte helfen, an Informationen zu gelangen	●	●	●	●	●

AttrakDiff

Nachfolgend stehen sieben Adjektivpaare, mit deren Hilfe Sie ihr Erleben dieses Bedienkonzepts beschreiben können. Diese Wortpaare stellen jeweils extreme Gegensätze dar, zwischen denen jedoch eine Abstufung möglich ist. Denken Sie nicht lange über die Wortpaare nach, sondern geben Sie bitte einfach direkt ihre Einschätzung ab. Es gibt keine „richtigen" oder „falschen" Antworten – nur Ihre persönliche Meinung zählt.

3 [AD1] *

Bitte wählen Sie die zutreffende Antwort für jeden Punkt aus:

technisch	●	●	●	●	●	●	●	menschlich
kompliziert	●	●	●	●	●	●	●	einfach
unpraktisch	●	●	●	●	●	●	●	praktisch
umständlich	●	●	●	●	●	●	●	direkt
unberechenbar	●	●	●	●	●	●	●	voraussagbar
verwirrend	●	●	●	●	●	●	●	übersichtlich
widerspenstig	●	●	●	●	●	●	●	handhabbar

4 [AD2] *

Bitte wählen Sie die zutreffende Antwort für jeden Punkt aus:

isolierend	●	●	●	●	●	●	●	verbindend
laienhaft	●	●	●	●	●	●	●	fachmännisch
stillos	●	●	●	●	●	●	●	stilvoll
minderwertig	●	●	●	●	●	●	●	wertvoll
ausgrenzend	●	●	●	●	●	●	●	einbeziehend
trennt mich	●	●	●	●	●	●	●	bringt mich näher
nicht vorzeigbar	●	●	●	●	●	●	●	vorzeigbar

5 [AD3] *

Bitte wählen Sie die zutreffende Antwort für jeden Punkt aus:

konventionell	●	●	●	●	●	●	●	originell
phantasielos	●	●	●	●	●	●	●	kreativ
vorsichtig	●	●	●	●	●	●	●	mutig
konservativ	●	●	●	●	●	●	●	innovativ
lahm	●	●	●	●	●	●	●	fesselnd
harmlos	●	●	●	●	●	●	●	herausfordernd
herkömmlich	●	●	●	●	●	●	●	neuartig

6 [AD4] *

Bitte wählen Sie die zutreffende Antwort für jeden Punkt aus:

unangenehm	●	●	●	●	●	●	●	angenehm
hässlich	●	●	●	●	●	●	●	schön
unsympathisch	●	●	●	●	●	●	●	sympathisch
zurückweisend	●	●	●	●	●	●	●	einladend
schlecht	●	●	●	●	●	●	●	gut
abstoßend	●	●	●	●	●	●	●	anziehend
entmutigend	●	●	●	●	●	●	●	motivierend

7 [P1] *

Bitte wählen Sie die zutreffende Antwort für jeden Punkt aus:

	stimme gar nicht zu			Teils/Teils			stimme voll zu
Insgesamt bin ich zufrieden, wie leicht diese Art, zwischen den Maschinen zu wechseln, zu bedienen ist	●	●	●	●	●	●	●
Es war einfach, diese Art zwischen den Maschinen zu wechseln, zu bedienen	●	●	●	●	●	●	●
Mit Hilfe dieser Art, zwischen den Maschinen zu wechseln, konnte ich die Aufgaben effektiv erledigen	●	●	●	●	●	●	●
Mit Hilfe dieser Art, zwischen den Maschinen zu wechseln, konnte ich die Aufgaben schnell erledigen	●	●	●	●	●	●	●
Mit Hilfe dieser Art, zwischen den Maschinen zu wechseln, konnte ich die Aufgaben effizient erledigen	●	●	●	●	●	●	●
Bei der Bedienung dieser Art, zwischen den Maschinen zu wechseln, fühlte ich mich wohl	●	●	●	●	●	●	●
Diese Art, zwischen den Maschinen zu wechseln, war leicht zu erlernen	●	●	●	●	●	●	●
Ich glaube ich könnte diese Art, zwischen den Maschinen zu wechseln, schnell produktiv einsetzen	●	●	●	●	●	●	●
Mit dieser Art, zwischen den Maschinen zu wechseln, bin ich insgesamt zufrieden	●	●	●	●	●	●	●

8 [P1E] *

Bitte wählen Sie die zutreffende Antwort für jeden Punkt aus:

	stimme gar nicht zu			Teils/Teils			stimme voll zu
Ich denke, dass die meisten Leute sehr schnell lernen würden, mit dieser Art, zwischen den Maschinen zu wechseln, umzugehen	●	●	●	●	●	●	●
Ich denke, die meisten Leute könnten mit dieser Art, zwischen den Maschinen zu wechseln, über längere Zeit ohne Fehleingaben arbeiten	●	●	●	●	●	●	●
Ich fand diese Art, zwischen den Maschinen zu wechseln, mühsam im Gebrauch	●	●	●	●	●	●	●

9 [P1T]Haben Sie weitere Anmerkungen?

Bitte geben Sie Ihre Antwort hier ein:

Vergleich

2 [VG1]Welche Art, zwischen den Maschinen zu wechseln, würden Sie am ehesten nutzen, falls Sie ein Arbeiter im vorgestellten Szenario wären? *

Bitte wählen Sie nur eine der folgenden Antworten aus:

- Den Wechsel per Reiter/Tabs
- Den Wechsel per Reiter/Tabs mit zusätzlicher Navigation mit Pfeilen
- Den Wechsel durch Zurückkehren in das Start/Home Menü
- Den Wechsel per Wischen mit zusätzlichem Direktwechsel über Buttons
- Den Wechsel durch kontinuierliches Scrollen der Detailansichten
- Den Wechsel durch Zoom In/Out mit zusätzlicher Navigation durch Wischen

3 [VG1]Welche Art, zwischen den Maschinen zu wechseln, würden Sie nicht nutzen wollen, falls Sie ein Arbeiter im vorgestellten Szenario wären? *

Bitte wählen Sie nur eine der folgenden Antworten aus:

- Den Wechsel per Reiter/Tabs
- Den Wechsel per Reiter/Tabs mit zusätzlicher Navigation mit Pfeilen
- Den Wechsel durch Zurückkehren in das Start/Home Menü
- Den Wechsel per Wischen mit zusätzlichem Direktwechsel über Buttons
- Den Wechsel durch kontinuierliches Scrollen der Detailansichten
- Den Wechsel durch Zoom In/Out mit zusätzlicher Navigation durch Wischen