Navigation in the Real World and in Virtual Worlds

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Abstract

Navigation is movement through an environment and involves locomotion and wayfinding in varying degrees. This applies to navigation in the real world as well as to navigation in virtual worlds. The requirements on user interfaces for real-world-navigation and virtual-world-navigation are similar but differ in priorities. For navigation in the real world, the most important aspect is usually to reach a destination as fast as possible without getting lost. For navigation in virtual worlds, the user experience is the central requirement, with a focus on entertainment for navigation in games.

This work aims at taking advantage of modern input technology to design natural and intuitive interaction concepts for navigation in the real world and navigation in virtual worlds. It explores motion-based navigation interfaces for mobile devices through three studies in the field of pedestrian navigation and two studies in the area of games. The results show that both real-world-navigation and virtual-world-navigation can benefit, but that motion-based interfaces have to be very carefully designed. Ambiguous feedback suggests to allow the user to switch between different interaction techniques.

In the field of pedestrian navigation, studies have shown advantages of image-based approaches. Panoramic photographs take it to the next level and offer contextual information. The research in the present dissertation explores the benefits of panoramas over simple photographs. Through two users studies in a realistic pedestrian navigation scenario, it shows that pedestrians clearly benefit from contextual information provided by panoramic images when navigating – regardless of whether they are combined with a map or not.

In the future navigation is expected to play an important role in the day-to-day use of smartwatches. Map apps for smartwatches present new challenges in cartography, a domain in which large display sizes have significant advantages. This work presents a novel cartographic approach that adapts the mobile web design technique of linearization to display maps on small screens. It transforms any two-dimensional route map into a one-dimensional "stripe". The results of a user study show that this simplification approach outperforms both traditional mobile map interfaces and turn-by-turn directions for pedestrian navigation using smartwatches.

Mobile interaction concepts for virtual exploration and games are challenging. Due to the lack of input devices, most of the interaction has to be realized on small sized touch screens. This work presents a novel control concept for virtual exploration and mobile games by integrating a physical pitch gesture and touch interaction. It uses a different meaning of touch depending on the device's orientation and a corresponding view in the virtual world. Through a user study the work demonstrates, that users understand and are able to employ interfaces based on a different meaning of touch and do not have any problem with switching between different input mappings.

In the area of games, where fun and the emotional experience are often more important than pure efficiency, it is important to investigate trade-offs between different input technologies. The research in the present dissertation investigates the importance of user experience and subjective efficiency. The results of two studies in the context of mobile gaming are ambiguous. While in one study the players preferred simple touch and motion-based interaction over more efficient software buttons, in another study the players preferred a virtual joystick over more intuitive alternatives because it is well-known, simple and precise.

Keywords *mobile human-computer interaction (mobile HCI), pedestrian navigation, virtual exploration, mobile games, virtual reality (VR), augmented reality (AR)*

Zusammenfassung

Navigation ist das Bewegen durch eine Umgebung und umfasst Fortbewegung und Wegfindung in unterschiedlichen Ausprägungen. Dies gilt sowohl für die Navigation in der realen Welt als auch für die Navigation in virtuellen Welten. Die Anforderungen an Benutzungsschnittstellen für Real-Welt-Navigation und Navigation in virtuellen Welten sind ähnlich, unterscheiden sich aber hinsichtlich der Prioritäten. Bei der Navigation in der realen Welt ist der wichtigste Aspekt in der Regel, ein Ziel so schnell wie möglich zu erreichen ohne vom Weg abzukommen. Bei der Navigation in virtuellen Welten ist das Nutzungserlebnis die zentrale Anforderung, mit einem Fokus auf dem Unterhaltungswert bei Spielen.

Ziel dieser Arbeit ist es, sich moderne Eingabetechnologien zunutze zu machen um natürliche und intuitive Interaktionskonzepte für die Navigation in der realen Welt und die Navigation in virtuellen Welten zu entwerfen. Es werden bewegungsbasierte Benutzungsschnittstellen zur Navigation auf Mobilgeräten im Rahmen von drei Studien im Bereich der Fußgängernavigation und zwei Studien im Bereich von Spielen untersucht. Die Ergebnisse zeigen, dass sowohl Real-Welt-Navigation als auch Navigation in virtuellen Welten davon profitieren können. Bewegungsbasierte Benutzungsschnittstellen müssen aber sehr vorsichtig eingesetzt werden. Mehrdeutige Reaktionen legen nahe, es dem Nutzer zu ermöglichen zwischen unterschiedlichen Interaktionstechniken wählen zu können.

Im Bereich der Fußgängernavigation haben Studien die Vorteile bildbasierter Ansätze aufgezeigt. Panoramafotografien gehen einen Schritt weiter und bieten kontextuelle Informationen. Die Forschung der vorliegenden Dissertation beschäftigt sich mit den Vorteilen von Panoramen gegenüber einfachen Fotografien. Mittels zweier Nutzerstudien in einem realistischen Szenario für Fußgängernavigation wird gezeigt, dass Fußgänger bei der Navigation von Panoramafotografien profitieren – unabhängig davon ob diese mit einer Karte kombiniert werden oder nicht.

Für die Zukunft ist zu erwarten, dass Smartwatches eine große Rolle bei der tagtäglichen Navigation spielen werden. Kartenanwendungen für

Smartwatches sind aus kartografischer Sicht eine Herausforderung, da im Bereich der Kartografie große Bildschirme von Vorteil sind. Diese Arbeit präsentiert einen neuartigen kartografischen Ansatz, der den im mobilen Web oft genutzten Prozess der Linearisierung aufgreift um Karten auf kleinen Bildschirmen anzuzeigen. Der Ansatz transformiert jede zweidimensionale Karte in einen eindimensionalen Streifen. Die Resultate einer Nutzerstudie zeigen, dass diese Vereinfachung sowohl traditionellen mobilen Benutzungsschnittstellen für Karten und Wegbeschreibungen von Punkt zu Punkt bei der Fußgängernavigation mit Smartwatches überlegen ist.

Mobile Interaktionskonzepte zur virtuellen Exploration und für Spiele sind eine Herausforderung. Auf Grund fehlender Eingabegeräte muss der Großteil der Interaktion auf kleinen berührungsempfindlichen Bildschirmen umgesetzt werden. Diese Arbeit präsentiert ein neuartiges Steuerungskonzept für die virtuelle Exploration und für mobile Spiele, das eine physikalische Neige-Geste mit berührungsempfindlichen Bildschirmen kombiniert. Das Konzept basiert auf unterschiedlichen Bedeutungen von Aktionen in Abhängigkeit von der Orientierung des Gerätes und einem entsprechenden Blick auf die virtuelle Welt. Mittels einer Nutzerstudie wird gezeigt, dass Nutzer derartige Benutzungsschnittstellen verstehen und in der Lage sind diese zu nutzen. Nutzer haben keine Probleme damit, zwischen unterschiedlichen Abbildungen der Berührungen zu wechseln.

Im Bereich von Spielen, bei denen Spaß und das emotionales Nutzungserlebnis oftmals wichtiger sind als die pure Effizienz, ist es von Bedeutung Kompromisse unterschiedlicher Eingabetechnologien zu untersuchen. Die Forschung der vorliegenden Dissertation untersucht die Bedeutung von Nutzungserlebnis und subjektiver Effizienz. Die Resultate von zwei Studien im Bereich mobiler Spiele sind mehrdeutig. Während in einer Studie die Spieler einfache Eingaben über berührungsempfindliche Bildschirme und Bewegungen gegenüber effizienteren Schaltflächen vorziehen, bevorzugen die Spieler in einer anderen Studie einen virtuellen Joystick gegenüber intuitiveren Alternativen weil dieser bekannt, einfach und präzise ist.

Schlagwörter *mobile Mensch-Computer-Interaktion (mobile MCI), Fußgängernavigation, virtuelle Exploration, mobile Spiele, Virtual Reality (VR), Augmented Reality (AR)*

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Contents

Part I

Summary of Research

Chapter 1

Introduction

"Navigation is coordinated and goal-directed movement through the environment [...]" (Montello, 2005). It involves *locomotion* and *wayfinding* in varying degrees. "Locomotion is body movement coordinated to the local surrounds; wayfinding is planning and decision making coordinated to the distal as well as local surrounds" (Montello, 2005). These characteristics applie to navigation in the *real world* as well as to navigation in *virtual worlds*.

Navigation in the real world and navigation in virtual worlds differ primarily in where the action takes place. Milgram et al. (1995) introduced the *Reality-Virtuality (RV) continuum* between real environments and virtual environments with mixed realities in-between. It can be applied for navigation in the real world and in virtual worlds to define a *Navigation Continuum (NC)* enclosing all variations of navigation (see Fig. 1.1). At the one extreme, pure real-world-navigation does not involve any digital helpers. An example is navigation using *paper maps*. At the other extreme, navigation completely in a virtual world happens without any physical action in the real world, e.g. using a *brain-computer interface (BCI)*.

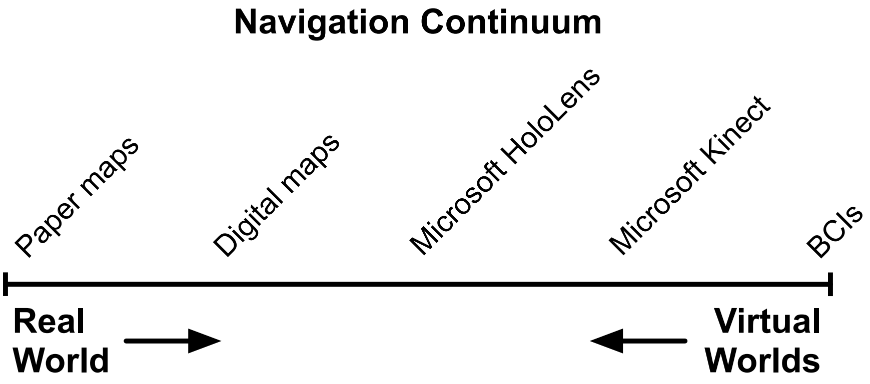


Figure 1.1 The *Navigation Continuum (NC)* with examples

The left area of the continuum encompasses navigation with the help of mobile devices: the user navigates in the real world but interacts with a virtual information space (e.g. a *digital map* on a smartphone). The right area encompasses interfaces for *Virtual Realities (VR)*; the user acts in the real world to navigate in a virtual world. Examples for motion-based VR interaction are interfaces using the *Mircosoft Kinect*. In the center, where real-world-navigation meets navigation in virtual worlds, concepts such as *Mircosoft's HoloLens* – a mixture between VR and *Augmented Reality (AR)* headsets – are located. Compared to AR, the proportion of virtuality is more extensive. The user does not only navigate in the real world but at the same time also in a virtual world, e.g. whole rooms can be turned into a virtual game.

The requirements on *user interfaces (UI)* for navigation in the real world and navigation in virtual worlds are similar but differ in priorities. For navigation in the real world, the most important aspect is usually to reach a destination as fast as possible without getting lost. While navigation systems should also provide a good user experience, for navigation in virtual worlds the user experience is the central requirement with a focus on entertainment for navigation in games. Finding the way does play a role in many games, but getting lost often is on purpose and the consequences are not serious. As a result, for each and every single navigation scenario, a suitable interface has to be found. The following research hypothesizes that all of them can benefit from natural and intuitive interaction. Thereby, *mental models* formed by navigation in the real world and *mappings* play an important role.

In the fields of *human-machine interaction (HMI)* and *human-computer interaction (HCI)* mental models are "[...] the models people have of themselves, others, the environments, and the things with which they interact. People form mental models through experience, training, and instruction." (Norman, 1988). Mappings are the relationships "[...] between the controls and their movements and the results in the world." (Norman, 1988). *Natural mappings* take "[...] advantage of physical analogies and cultural standards [...]" (Norman, 1988) and lead to immediate understanding. According to Wigdor and Wixon (2011), the term *natural* "[...] is a design philosophy and a source for metrics enabling an iterative process to create a product". They "see natural as referring to the way users interact with and feel about the product, [...] what they do and how they feel while they are using it". The term *intuitive* is closely related. Technical systems are "[...] intuitively usable while the particular user is able to interact effectively, not-consciously using previous knowledge" (Naumann et al., 2007). Thereby, "[...] intuitive use can only be attributed to the human-machine interaction in a certain context [...], but not to a technical system per se" (Naumann et al., 2007).

Modern input technology allows natural and intuitive interfaces based on the user's motions. Today's mobile devices come with a variety of sensors (e.g. accelerometers, gyroscopes and magnetometers) which can be used to determine the device's position and orientation. Mobile interfaces based on this information are called *spatially-aware displays* (Fitzmaurice, 1993). Spatially-aware displays implement an eye-in-hand metaphor and act as windows onto the virtual information space. They respond to the user's movements and "[...] serve as a bridge or porthole between computer-synthesized information spaces and physical objects" (Fitzmaurice, 1993). *Peephole interfaces* (Yee, 2003) augment the space around the user with information. They "[...] fall into the category of spatially aware displays, which differ [...] in that they create a positional mapping between the virtual space and the real world, enabling the use of spatial memory for navigation" (Yee, 2003). The following research focuses on taking advantage of motion input technology to design natural and intuitive interaction concepts for navigation in the real world and navigation in virtual worlds. For navigation in the real world, the research aims at interfaces which are easy-to-understand, easy-to-use and effective. For navigation in virtual worlds, the research additionally aims at entertaining interfaces. In the following, five hypotheses are formulated. They will be discussed in Chapter 6. The main hypothesis is:

H_1 Navigation in the real world and navigation in virtual worlds benefit from natural and intuitive interaction concepts based on the user's motions.

This general hypothesis cannot be proven or disproven as such, but for selected use cases along the *Navigation Continuum* interaction prototypes can be developed and evaluated to gain a better understanding of the hypothesis' validity. For navigation in the real world, the research is focused on *pedestrian navigation*. For navigation in virtual worlds, the focus is on *virtual exploration* and *games* on mobile devices.

1.1 Pedestrian Navigation

Pedestrian navigation is a challenge for mobile human-computer interaction and represents a complex problem of contextual interaction in complex and dynamic environments. In contrast to car navigation where the users are surrounded with technology, pedestrians have to interact actively with a device. They need to switch attention between the surroundings and the device while performing the task of walking in a dynamic urban space. While today pedestrians first and foremost use navigation systems on smartphones, in the future navigation is expected to play an important role in the day-to-day use of smartwatches.

Studies investigating pedestrian navigation with mobile devices have shown the benefits of images; standalone (Walther-Franks and Malaka, 2008) or combined with maps (Beeharee and Steed, 2006; Chittaro and Burigat, 2005; Goodman et al., 2005). Images quickly transport detailed visual instructions and allow the user to simply map integrated route information onto the physical world. Maps give a brief and generalized overview of the surroundings at the cost of mental effort. When combined, the context of the route presented by the map complements with the focus on a single navigation step provided by images taken at waypoints. Modern mobile devices allow to bundle the advantages of both and to assemble maps, images and sensor data into a pedestrian navigation system. Apart from the *Global Positioning System (GPS)*, cellular networks and WiFi to determine the user's current position, built-in inertial sensors such as accelerometers and a digital compass can be used for natural and intuitive interaction. Panoramic photographs take it to the next level and offer additional contextual information.

Particularly in the context of pedestrian navigation, smartwatches do have important benefits over smartphones. Navigation on smartphones requires keeping the device in one's hands at all times, while both hands can remain mostly free when navigating via a smartwatch. Before smartwatch navigation systems can meet their potential, some important cartographic challenges have to be addressed which arise from the very small screen size on smartwatches.

In addition to natural and intuitive interaction concepts, the following research on pedestrian navigation investigates image-based navigation on mobile devices and map-based navigation on smartwatches. The hypotheses are:

H_2 Pedestrians benefit from contextual information provided by panoramic images when navigating.

H_3 Novel cartographic approaches for small screens improve map-based pedestrian navigation on smartwatches.

1.2 Virtual Exploration and Games

Services for the virtual exploration of physical environments such as urban areas, also called remote viewing or remote exploration, are widespread and often used. One of the first systems was *Movie-Maps* (Lippman, 1980). *Movie-Maps* was based on photographs and allowed the user to virtually explore distant places via touchscreen or joystick. The first commercially successful image-based remote exploration software was Apple's *QuickTime VR* (Chen, 1995). Comparable to today's *Google Street View* (Vincent, 2007; Anguelov et al., 2010), QuickTime VR allowed the user to look around in cylindrical 360° panoramic images and to move through the virtual world by jumping between the images. Today, especially mapping services are of importance. They are not only used for navigation tasks en route, but also for virtual exploration at home. To support the user with additional information about virtually visited areas, most of the providers augment their maps with photographs, panoramic images or 3D models of buildings; either in a second view or integrated into the map. In virtual globes such as Google Earth 3D worlds are built by mixing different kinds of media and other data (e.g. satellite imagery, elevation data and 3D models). Virtual-world-navigation is mostly found in games. The powerful hardware of mobile devices enables game developers to create complex and extensive 3D worlds. In contrast to stationary gaming consoles, smartphones and tablets have a lack of complex, specialized input devices. Therefore, most of the interaction has to be realized on small sized touchscreens.

Currently, mobile interaction concepts are either based on touch or on physical gestures. The interaction is often limited to offer a simple and easy-to-use interface. Combining touch and motion input has the advantage of allowing more complex interfaces for navigating in virtual worlds. The approach can also be used for AR games, which require the player to keep the AR world in view at all times.

For both virtual exploration and games, the following research investigates interaction concepts combining motion and touch input for navigation in virtual worlds. Furthermore, it investigates the importance of user experience for mobile games. The additional hypotheses are:

H_4 Users understand and are able to employ interfaces based on a different meaning of touch depending on the mobile device's orientation.

H_5 In the context of gaming, user experience is more important than subjective efficiency.

Currently, many companies are developing VR headsets (e.g. the *Oculust Rift*) for the mass market. Therefore, the following research also presents an outlook on physical locomotion interfaces for navigation in virtual realities.

1.3 Structure of the Document

The work is based on a number of scientific publications. While Part I of this document summarizes the research and highlights the most important findings, Part II includes all publications the summary is based on.

Part I first introduces related work (Chapter 2). The rest of this part is structured as follows (Fig. 1.2 shows the sections in the NC):

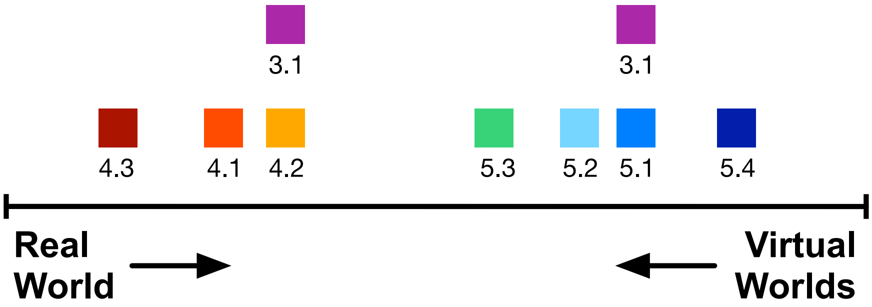


Figure 1.2 The document's sections in the NC

Chapter 3 presents a natural and intuitive interaction concept based on motion for both pedestrian navigation and virtual exploration. Specifically, the research in Section 3.1 (🟪 Interaction with Combinations of Maps and Images) proposes to use a physical *pitch gesture* combined with a *peephole interface* to interact with combinations of maps and images on mobile devices.

Chapter 4 explores pedestrian navigation. The research in Section 4.1 (🟥 Panoramic Photographs for Image-based Navigation) explores the benefits of panoramic photographs over simple photographs for image-based navigation. Furthermore, it compares *peephole interaction* for panoramic images against a touch-based interface. In Section 4.2 (🟧 Navigation with Combinations of Maps and Images), navigation based on maps and images is explored. First, the *pitch gesture* to switch between an image view and a map is compared against touch-based interaction. Second, *manual switching* of views is evaluated vis à vis a *split screen* in two variants: one employing panoramic images aligned to the device's orientation and one using simple photographs. The research in Section 4.3 (🟥 Map-based Navigation on Smartwatches) aims at improving pedestrian navigation on smartwatches. It presents a novel cartographic approach adapting the mobile web design technique of linearization to display maps on smartwatches' small screens. Two variants of the system are evaluated against turn-by-turn navigation and the traditional 2D maps on smartwatches. One of them provides an orientation indicator: using the smartwatch's built-in compass it shows the direction for the currently displayed route segment.

Chapter 5 investigates virtual exploration and games with a focus on mobile devices. The research in Section 5.1 (🟦 Exploring Combinations of Maps and Images) proposes to combine the *pitch gesture* with a *different meaning of touch* – depending on the device's orientation – to explore combinations of maps and images for virtual exploration. The research in Section 5.2 (🟦 Indirect Sensor Control for Mobile Gaming) brings this idea to mobile games and evaluates it against traditional software buttons in a labyrinth game. Furthermore, it explores the importance of user experience and subjective efficiency in the context of gaming. In Section 5.3 (🟩 Avatar Control in AR Games), interaction concepts to control an avatar in an AR game are explored. One of them requires the player to move in the real world to control a character in the virtual world. The research in Section 5.4 (🟦 Physical Locomotion) explores natural navigation in virtual worlds beyond mobile devices and presents a novel physical locomotion interface for virtual environments.

Finally, Chapter 6 discusses all the insights on navigation in the real world and navigation in virtual worlds and presents the conclusion.

Chapter 2

Related Work

This work draws from and builds on research in the domains of pedestrian navigation, virtual exploration, games and physical locomotion. In the following, related work from each of these domains will be discussed.

2.1 Pedestrian Navigation

Work on map-based mobile guides dates back almost two decades. Initially, mobile guides and pedestrian navigation systems focused on maps to provide route information. The *Cyberguide* (Abowd et al., 1997) used a schematic map which was automatically updated based on the user's position. It worked both outdoors and indoors: while outdoors the position was determined using GPS, inside buildings infrared sensors were used. Goal of the *GUIDE* (Cheverst et al., 2000) project was to build a mobile tourist guide for the city of Lancaster. It allowed the user to switch between an overview map and a map of the local area. Malaka and Zipf (2000) developed a mobile tourist information system which included navigation functionality. It presented animated route information using a 3D city model. For an overview of early map-based mobile guides see Baus et al. (2005), Huang and Gartner (2010) provide a survey focused on indoor navigation systems.

2.1.1 Image-based Navigation

Early work in the field of pedestrian navigation demonstrated the supporting value of images augmenting auditive hints and maps (Chittaro and Burigat, 2005) or combined with textual instructions and maps (Beeharee and Steed, 2006). While Chittaro and Burigat (2005) automatically replaced the map view with an image view in particular situations, Beeharee and Steed (2006) allowed the user to manually switch between both views. Goodman et al. (2004) and Goodman et al. (2005) used photographs in a navigation system for older people. Although the participants of a field experiment preferred to use both audio and images (Goodman et al., 2004), in another experiment landmarks pictured on images performed better than landmarks presented by speech (Goodman et al., 2005). Kaminoyama et al. (2007) developed an image-based navigation system for people with early-stage dementia. In user studies, dementia sufferers (simulated with children aged between eight and nine years) as well as healthy people needed less time to complete navigation tasks. Walther-Franks and Malaka (2008) used simple photographs augmented with visual instructions to guide users incrementally from waypoint to waypoint.

The most successful commercial system is the navigation feature of *Google Street View* which uses 360° panoramic images. The benefits of panoramic images compared to simple photographs have not been explored yet. This is also true for interfaces to browse panoramas in the context of pedestrian navigation. Furthermore, no work has compared different approaches of combining maps and images.

2.1.2 Visualizations

Visualizing navigation routes and instructions is a critical aspect in designing mobile navigation systems. Kray et al. (2003) distinguish between textual and spoken instructions, 2D route sketches including simple arrows, 2D maps and pseudo realistic instructions such as 3D maps in different levels of abstraction. They recommend that the choice of the instructions depends on the availability of location, orientation, cognitive and technical resources. Similar, Puikkonen et al. (2009) evaluated different map designs for indoor navigation. Schöning et al. (2014) inspected a large dataset of publicly-displayed local maps to identify design decisions made by cartographers to inform the design of online and mobile maps. Recently, Alvina et al. (2014) presented *RouteLenses*. They aim at making it easier for users of online maps to follow map itineraries by dynamically adapting properties of the motor space, based on both cursor position and route geometry.

May et al. (2003) point out that pedestrians orientate themselves towards prominent landmarks instead of street names or distance measurements. For image-based navigation, Walther-Franks and Malaka (2008) found out that people prefer path visualizations over arrows in simple photographs.

2.1.3 Interfaces

Besides different visualizations of route descriptions and maps, developing novel interfaces to support indoor and outdoor navigation is an important research field within the area of HCI. Especially inertial sensors allow new interaction concepts for pedestrian navigation systems. Seager and Fraser (2007) investigated automatic map rotation using a digital compass. In a field experiment, they compared physical, automatic and manual rotation against north-up maps. While physical rotation was the most effective probably because there is no need for mental mapping, Seager and Fraser (2007) suggested to use automatic rotation for turn-by-turn–based instructions.

Kolbe (2004) proposed to align panoramic images using an orientation sensor. This is based on the idea of *spatially-aware displays* introduced by Fitzmaurice (1993). Spatially-aware displays act as windows onto the virtual information space by implementing an eye-in-hand metaphor. Because they are aware of both their physical position and orientation in space, spatially-aware displays are able to respond to the user's movements. They serve as a bridge between computer-synthesized spaces and the physical world. Yee (2003) extended spatially-aware displays by creating a positional mapping between the virtual space and the real world. The concept was called *peephole display*, because it augments the space around the user with information. Mehra et al. (2006) related peephole displays with other techniques to browse information spaces and distinguished between static peepholes and dynamic peepholes. Traditional panning and zooming interfaces are static peepholes because a dynamic information space is moved behind a static display. In contrast, Yee's concept is a dynamic peephole because the user browses a static information space by his movements. In an evaluation by Hürst and Bilyalov (2010) dynamic peepholes performed better than static peepholes in orientation and object size discrimination tasks and were preferred by 80% of the users.

Other researchers investigated AR-based navigation. For example, Mulloni et al. (2011) presented a design of a mobile AR interface to support indoor navigation. Recently, Möller et al. (2014) evaluated mobile user interfaces for visual indoor navigation containing virtual and augmented reality elements.

Reilly et al. (2009) focused on how to use mobile devices with paper maps to express queries and present dynamic information for navigation and planning purposes to overcome small screen problems that occur when displaying maps on mobile devices.

2.1.4 Navigation with Wearables

Besides the use of mobile devices to support navigation, researchers and practitioners have also explored navigation on various wearable devices, although none have investigated the efficacy of different cartographic approaches. Interestingly, some of the early map-based mobile guides made use of wrist-worn map interfaces. For instance, the *DeepMap* system (Malaka and Zipf, 2000) presented animated route information on a wrist-mounted display. Pielot et al. (2009) explored the use of a vibrotactile belt to continuously indicate a destination's direction relative to the user's orientation. McGookin and Brewster (2013) focused on supporting undirected navigation for runners in a system called *RunNav*, which could also be used on a smartwatch. Rather than offering explicit routes, RunNav provides a high-level overview of an area to allow for serendipity while at the same time informing runners of areas that are generally good and bad places to run.

On the practitioner side of things, *Google's Android Wear* supports turn-by-turn navigation while *Google Glass* additionally supports visualizing route information on maps.

2.1.5 Small Screen Visualization and Interaction

As screen space is very limited on smartwatches and the "fat finger problem" (Siek et al., 2005) heavily impacts the interaction, most work regarding smartwatch interaction explores additional input techniques or modalities (Chen et al., 2014; Kim et al., 2007). For example, Rekimoto (1996) investigated the use of tilting as an additional input modality. As a smartwatch worn on the wrist can be turned in all directions, his findings could fully be applied to smartwatches. Similar, the work of Xiao et al. (2014) is concerned with expanding the input expressivity of smartwatches with mechanical pan, twist, tilt and click. To extend the input space on smartwatches, Ashbrook et al. (2008) investigated the interaction on a circular touchscreen wristwatch in depth. Oakley and Lee (2014) addressed the "fat finger problem" by sensing touches to the perpendicular edges of a device. Kerber et al. (2014) demonstrated how smartwatches could be used as magic lenses to browse through maps, but also showed that this technique does not outperform a "classical" UI.

2.2 Virtual Exploration

One of the first systems for virtual exploration was *Movie-Maps* by Lippman (1980), which allowed the user to remotely explore existing places using photographs stored on a video disc. Movie-Maps supported interaction with a touchscreen or a joystick. The first commercially successful image-based remote exploration software was Apple's *QuickTime VR* (Chen, 1995). QuickTime VR allows the user to look around in cylindrical 360° panoramic images. Comparable to today's *Google Street View* (Vincent, 2007; Anguelov et al., 2010), the user moves through the virtual world by jumping between the images. The *Fly-About* project (Kimber et al., 2001) was based on cylindrical panorama videos which were captured continuously along a predefined path. The user was able to play the interactive video using a map-based interface. *Street Slide* (Kopf et al., 2010) used multi-perspective photographs taken at several points along a path. It allows to picture a whole street of houses in one single photograph. *m-LOMA* (Nurminen, 2006), a mobile portal for location-based information, was one of the first projects integrating a 3D city model in an application for mobile devices. The most popular and successful related project is the virtual globe *Google Earth* (Anguelov et al., 2010), which is available for desktop PC and mobile devices.

2.2.1 Mobile 3D Interaction

3D environments require *spatial input* with up to six degrees of freedom (*3D interaction*). Hinckley et al. (1994) offered an overview of different approaches and discussed general problems of spatial input. The result are design guidelines for 3D user interfaces. Touchscreens were only a minor aspect. Nurminen and Oulasvirta (2008) investigated the navigation through 3D maps on mobile devices focusing on degrees of freedom (DOF). They concluded that the main challenge on designing 3D user interfaces is a tradeoff between free movements and efficiency achieved by limited and guided navigation. The results are interface guidelines for mobile devices with touchscreen, a small number of hardware buttons and a directional pad.

Before first smartphones with built-in orientation sensors entered the market, Mountain and Liarokapis (2005) proposed to combine mobile devices with different types of sensors to enhance the mobile interaction in virtual environments. One aspect was to switch between a top-down view and a view from the bottom by physically tilting the device. Benzina et al. (2011) used a smartphone as 3D input device to realize one-handed navigation in virtual environments. It allows the user to translate the view via the touchscreen while for rotation the built-in inertial sensors were used. The concept clearly distinguishes between interaction for translation and interaction for rotation.

Furthermore, de facto standards for touchscreen interaction have been established. Map apps such as *Google Maps* for mobile devices translate the map when the user touches the screen. Panoramic image apps (e.g. *Google's Street View*) link touchscreen input to view rotation. *Google Earth* for mobiles combines both; it allows the user to switch between translation and rotation via a software button. There are no approaches, neither by researchers nor by practitioners, to combine physical interaction with a different meaning of touch depending on the device's orientation for navigation. This is also true for games.

2.3 Mobile Games

While some studies suggest that hardware buttons and keyboards are generally preferred by users compared to touch input (Wong et al., 2010; Chu and Wong, 2011), the same studies also hint at the great potential of touch interaction. Today, hardware keyboards are no longer available on the majority of mobile devices. An alternative is to improve touch interaction with the help of additional input data, e.g. from inertial sensors. This approach follows the findings and the design guidelines of Salo et al. (2012), who state that minimizing the number of on-screen control elements is very important. Duh et al. (2008) recommend to design specific types of games for different mobile phone interfaces.

2.3.1 Tilt Interaction

Tilt interaction is ubiquitous on today's mobile devices but the application-specific impact is still not completely explored. Especially, in the area of games, where fun and the emotional experience are often more important than pure efficiency it is important to further investigate the trade-off between different input technologies. While studies investigated the use of tilt gestures for mobile gaming (Gilbertson et al., 2008; Chehimi and Coulton, 2008) or compared tilting gestures to keypad (Tonder and Wesson, 2011) or touch input (Browne and Anand, 2012), none of them employed tilting gestures for switching between different view types with specific input mappings. Browne and Anand (2012) found that players prefer accelerometer-based interaction to touch gestures and touch buttons but also note that multiple user interfaces should be available.

2.3.2 Augmented Reality

Oda et al. (2007) extended an existing car racing game by adding an augmented reality component. They used computer-vision–based fiducial marker tracking for both the physical gameboard and the controllers (pairs of bicycle handlebars). Harviainen et al. (2009) used camera movements and accelerometers to control virtual characters. In one example an animated model of a dog reacts to the camera's movements, while another approach used the accelerometer to detect shaking or tilting of the phone. Hürst and Wezel (2011) developed interface concepts for mobile AR apps and used the camera to track a marker attached the user's finger tip. This allows direct interaction with virtual objects. For the users, it was a challenge was to keep the device steady while moving the finger. Lagerstam et al. (2012) tested camera-based interaction techniques with an AR application for children aged 10 to 11. Their results suggest that the mental overhead of both keeping a marker in the camera's field of view and trying to control some avatar in the AR world at the same time might be too high for children of this age. Gu et al. (2011) developed an AR game in which two players can fight each other in a virtual arena. To enhance the game interactivity, the accelerometer was used to control the characters. They did not compare different approaches for controls.

2.4 Physical Locomotion

Physical locomotion techniques employ the user's body motion to facilitate moving through virtual environments. The physical exertion of the user has been shown to increase the self-perceived sense of presence in comparison to sedentary techniques (Bowman et al., 2004). Virtual reality research distinguishes three categories: walking, *walking-in-place (WIP)* and devices simulating walking. Virtual travel interfaces using actual walking transfer the user's physical locomotion directly into the virtual space. These can only be used for small areas, due to the restricted tracking range of sensing devices.

WIP techniques require the user to imitate a walking motion on the spot. Although this does not require the full leg motions of real walking, it is a good compromise between completely virtual travel and real walking, supporting presence better than the former but less than the latter. Keeping recognition latency to a minimum poses a challenge for WIP interfaces. State of the art algorithms approach this matter with prediction heuristics based on biomechanics (Wendt et al., 2010). Simulation devices address the tradeoff between area constraints and natural motions by mechanically supporting the user in making full walking motions without actually moving. These devices range from treadmills to spheres (Medina et al., 2008) or low friction surfaces (Swapp et al., 2010). However, such devices often suffer from balance problems, lag or limiting the freedom of movement of the user.

Chapter 3

Mobile Interaction for Pedestrian Navigation and Virtual Exploration

This chapter presents an interaction concept for pedestrian navigation and virtual exploration. While studies have shown the advantages of map-image-combinations for pedestrian navigation, none of them focused on intuitive and natural interaction. The research in the following section proposes to combine a *pitch gesture* with the *peephole metaphor* and presents a prototype implementing the concepts. Both pedestrian navigation and virtual exploration should benefit.

3.1 Interaction with Combinations of Maps and Images

Dirk Wenig and Rainer Malaka (2010). "Interaction with Combinations of Maps and Images for Pedestrian Navigation and Virtual Exploration". In: *Proceedings of the 12th International Conference on Human Computer Interaction with Mobile Devices & Services*. MobileHCI '10. ACM, pp. 377–378. DOI: `10.1145/1851600.1851673`

Studies in the field of pedestrian navigation have shown advantages of map-image combinations (Beeharee and Steed, 2006; Chittaro and Burigat, 2005; Goodman et al., 2005). While Chittaro and Burigat (2005) automatically replaced the map view with the image view in particular situations, e.g. when approaching junctions, Beeharee and Steed (2006) allowed the user to manually switch between both views via touchscreen interaction.

In Interaction with Combinations of Maps and Images for Pedestrian Navigation and Virtual Exploration (Wenig and Malaka, 2010), we introduced an intuitive and natural interaction technique for combinations of maps and images for both pedestrian navigation and virtual exploration. Additionally, the publication presents a prototype for smartphones implementing the ideas.

3.1.1 Combining Maps and Images

Both quantitative and qualitative evaluations indicate an additional value of map-image-combinations for pedestrian navigation (Beeharee and Steed, 2006; Chittaro and Burigat, 2005). Maps give a brief and generalized overview; they present the context of the route at the cost of mental effort. An advantage of images is the focus on one navigation step, which allows detailed visual instructions. Intuitive and natural interaction is important to enable the user to utilize the additional value. We suggest pitching the device to switch between both views in combination with a peephole interface to browse the image content.

Pitching for View Switching While maps usually represent space from a bird's-eye view, images in pedestrian navigation use some kind of human's-eye view (Beeharee and Steed, 2006; Chittaro and Burigat, 2005; Walther-Franks and Malaka, 2008). By following the idea of spatially-aware displays, showing the map when the device lies in the user's hand while displaying the image content when the user holds the device on edge should be a natural mapping and an intuitive way of interaction (see Fig. 3.1). Furthermore, it allows easy and fast switching between both views.

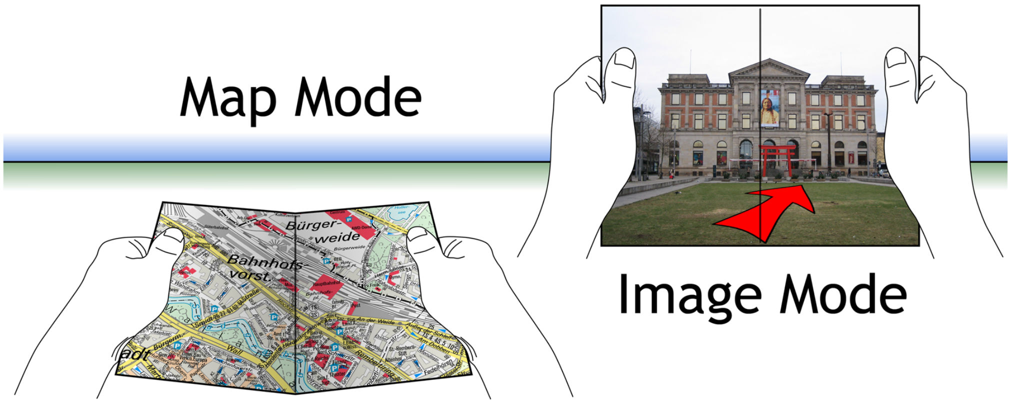


Figure 3.1 Idea of a pitch gesture

Peephole Interaction Because of the limited screen size, mobile devices can only show a small part of the virtual information space at once. Panning and zooming are typical interfaces that deal with these limitations. Situating geotagged image content on top of a map in the virtual information space allows a combination of the peephole metaphor (see Fig. 3.2) with the pitch gesture: pitching the device allows a continuous transition between the map view and the image view, by rotating their body users can align the map and browse through the image content. The direct relationship between the virtual space and the user's body minimizes the mental effort.

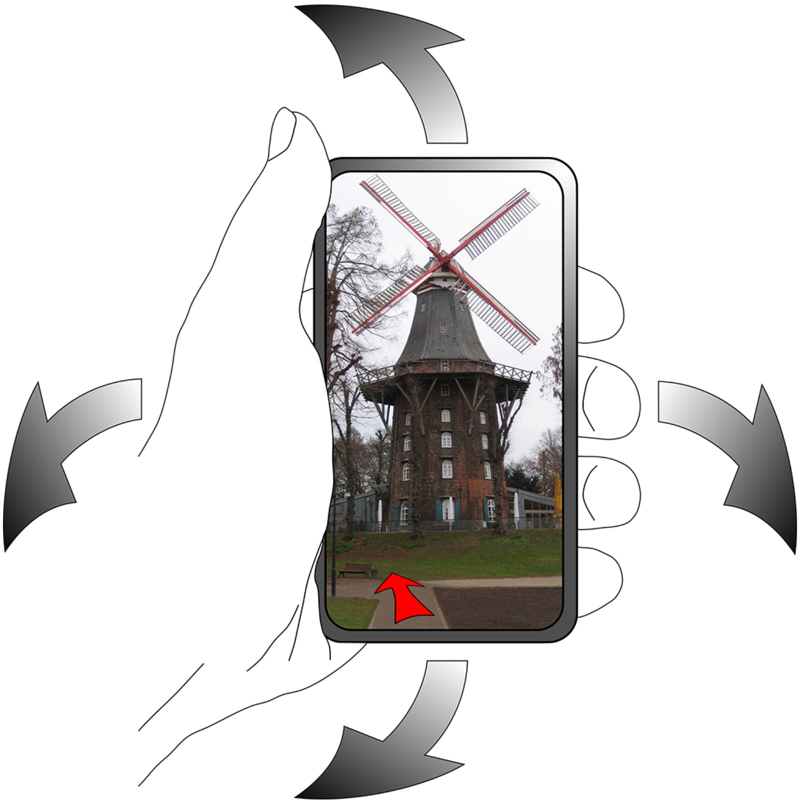
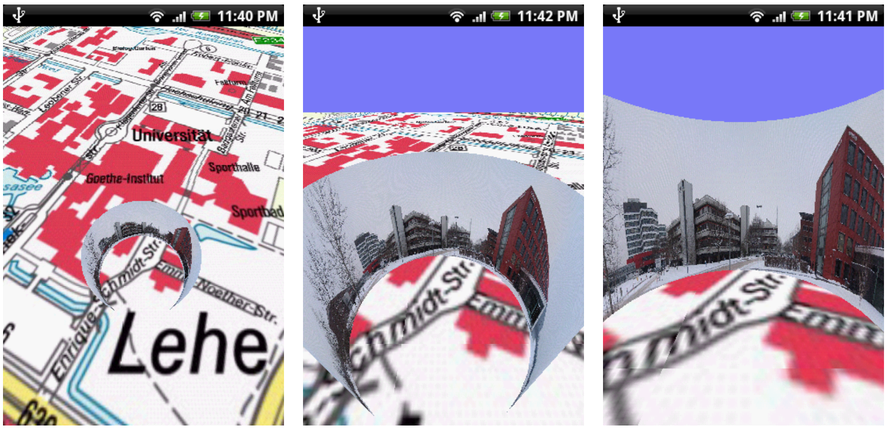


Figure 3.2 Peephole metaphor

3.1.2 Prototype

We developed a prototype (see Fig. 3.3) for the *HTC Hero* smartphone which uses a 3-axis accelerometer and a digital compass to determine its orientation. The prototype supports the presentation of a map and geotagged cylindrical panoramic photographs. It implements our interaction ideas as follows: on the one hand the user can pitch the device to switch continuously between the map and the images; on the other hand the prototype allows the user to rotate the view. Furthermore, touching the screen allows the user to pan the position.



(a) **(b)** **(c)**

Figure 3.3 Map view (a), transition (b) and image view (c)

3.1.3 Conclusion

The presented concept supports using the advantages of maps and images in an intuitive and natural way; not only for pedestrian navigation but also for virtual exploration with mobile devices. Informal user tests indicate a high usability and acceptance. Users learned very fast to use the prototype's functionality and seemed to have a lot of fun. Further research has to investigate in detail whether pitching the device is usable and whether dynamic peephole interaction and automatic map rotation fulfills the user's needs.

The publication Interaction with Combinations of Maps and Images for Pedestrian Navigation and Virtual Exploration in Part II provides details on the ideas and the prototype.

Chapter 4

Pedestrian Navigation

The research in the following chapter explores three different approaches for pedestrian navigation systems: panoramic photographs for image-based navigation, combinations of maps and images, and map-based navigation on smartwatches.

Studies have shown advantages of approaches using simple photographs for pedestrian navigation. Panoramic photographs take it to the next level and offer contextual information. Interaction supporting the user to utilize the additional value is required. The first of the following sections presents an evaluation of static and dynamic peephole interfaces for panoramic photographs and explores the benefits of panoramas over simple photographs in a realistic pedestrian navigation scenario.

Additionally, studies have shown advantages of map-image combinations. In previous work the map view was either replaced with an image view in predefined situations, or the user was required to manually switch between the two views by touch. The second section investigates alternative approaches. First, in a field study the pitch gesture for switching between the views is compared to touch-based interaction. Second, the section proposes to use a split screen displaying maps and images at the same time. Two variants were developed; one employing panoramic images aligned to the mobile device's orientation and one using simple photographs. In a second study, both were evaluated against manual switching.

Maps are expected to play an important role in the day-to-day use of smartwatches and have benefits over their smartphone equivalents, particularly in the context of pedestrian navigation. Using maps on a phone requires keeping it in one's hands at all times, while both hands can remain mostly free when navigating via a smartwatch. The third section presents *StripeMaps*, a system that adapts the mobile web design technique of linearization to display maps on smartwatches' small screens and transforms any two-dimensional route map into a one-dimensional "stripe". In a user study, StripeMaps was evaluated against traditional mobile map interfaces and turn-by-turn directions. Additionally, the section illuminates the advantages and drawbacks of traditional mobile maps and turn-by-turn directions on small screens.

4.1 Panoramic Photographs for Image-based Navigation

Dirk Wenig, Tim Nulpa, Rainer Malaka, and Michael Lawo (2012). "An Evaluation of Peephole Interaction with Panoramic Photographs for Pedestrian Navigation". In: *Proceedings of the Young Researchers Forum on Geographic Information Science.* Vol. 44. ifgiPrints / GI Zeitgeist 2012. Institut für Geoinformatik, Westfälische Wilhelms-Universität Münster. Akademische Verlagsgesellschaft AKA GmbH, pp. 23–32

Simple interaction suited for the scenario of pedestrian navigation is important to enable the user to utilize the contextual information provided by panoramic images. In addition to rotating the view by touching the screen (*static peephole*), modern smartphones allow the user to browse the panoramic photograph by moving the mobile device (*dynamic peephole*). The direct relationship between the panorama and the user's body minimizes the mental effort.

In An Evaluation of Peephole Interaction with Panoramic Photographs for Pedestrian Navigation (Wenig et al., 2012), we evaluated three approaches for pure image-based navigation in a real pedestrian navigation scenario: simple photographs, panoramic photographs with a static peephole interface, and panoramic photographs with a dynamic peephole interfaces. The goal was to validate the hypothesis that people benefit from the contextual information provided by panoramic photographs, and further to investigate which peephole interface is better suited for supporting the user to utilize the additional value.

4.1.1 Prototype

We developed three interaction prototypes implementing the three approaches. The prototypes are based on an app we built for the widespread *HTC Desire* smartphone. The app supports the presentation of spherical panoramic images and overlaying arrows providing route information (see Fig. 4.1). Using *GPS* the system offers a panoramic photograph whenever the user approaches a waypoint and notifies by a short sound and vibration.

The first interaction prototype simulates simple photographs. It presents the panoramic photograph and the arrow as described, but locks the view and does not allow any interaction. The panorama is vertically centered and horizontally aligned alongside the route. The second prototype implements a static peephole interface. Initially, it shows the same view as the first prototype does, but allows the user to rotate the panorama horizontally by touching the screen. The third prototype implements a dynamic peephole by registering the view with the smartphone's digital compass. Again, the panorama is vertically centered and interaction is limited to horizontal rotation.

(a) (b)

Figure 4.1 The prototype: different orientations of the same panorama

4.1.2 Field Study

We conducted a field study (between-group design) to investigate the three prototypes in a realistic pedestrian navigation scenario. Our research questions were:

(1) Do people benefit from the additional contextual information provided by panoramic photographs?

(2) Is static peephole interaction or dynamic peephole interaction better suited for supporting the user to utilize the additional value?

Participants and Route We recruited 15 volunteers with mixed knowledge of the surrounding area to test the three prototypes. The test route has successfully been used in previous experiments on image-based navigation (Walther-Franks and Malaka, 2008). It runs from outside the inner city into the historic center of Bremen (Germany) and is about 950 meters long (see Fig. 4.2). For each of the 15 waypoints along the path, a panoramic photograph was included in the prototypes and augmented with an arrow.

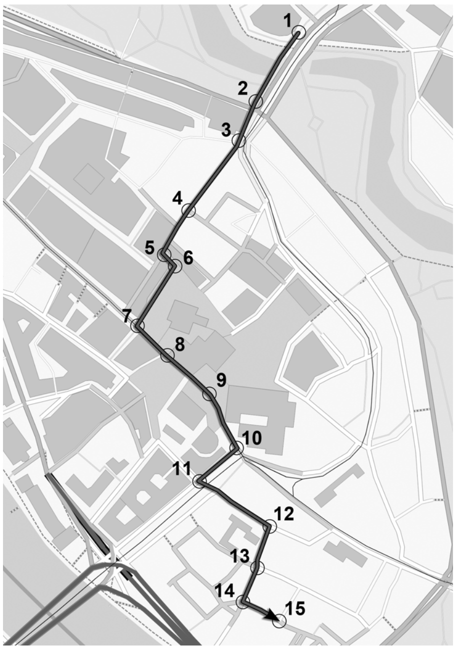


Figure 4.2 Test route the participants had to follow

Procedure During the test runs the supervisor followed a few steps behind without interrupting. Participants were asked to think aloud. We recorded the time participants needed to walk the route and to orientate themselves at waypoints. Furthermore, we counted one error if the user departed more than 20 meters from the path and sent him back to the last waypoint. In addition to noted observations, we used the System Usability Scale (SUS) (Brooke, 1996) questionnaire and two sets of the Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh et al., 2003) to estimate the user's attitude and anxiety towards the system.

4.1.3 Results

All users successfully completed the navigation task. Two errors occurred; a participant using the simple photograph-based prototype lost his way twice.

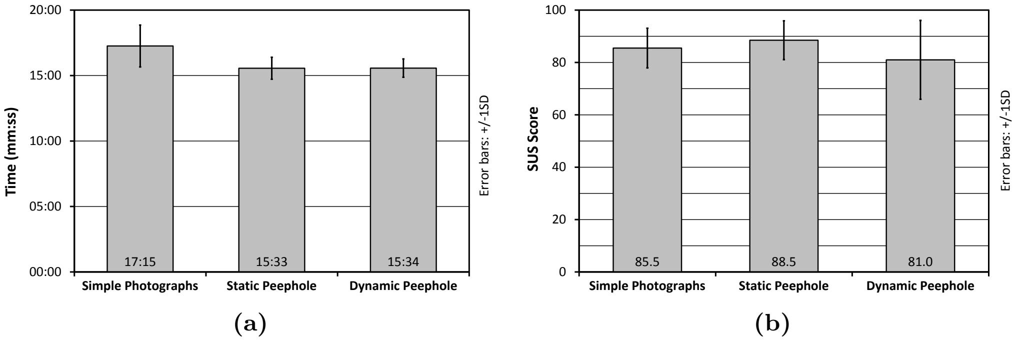


Figure 4.3 Walking speed corrected mean times (a) and mean SUS scores (b)

Observation All participants seemed to learn very fast how to use the prototypes. Observations suggested that participants using simple photographs took more time to orientate themselves at waypoints. They often searched for landmarks which were not pictured on the images, and seemed to recheck the waypoints more often while walking. The group using the static peephole looked around in the panorama at almost every waypoint and quickly found the landmarks they needed to decide where to go. In addition, they often took the opportunity to verify their decision before proceeding. Hence, the participants rarely rechecked the way while walking. When using the dynamic peephole, the participants often seemed to use it in the manner of a simple compass pointing at the next waypoint. They did not ignore the underlying panorama, but used it to identify the arrow's origin. Most of them were irritated that they had to rotate themselves for orientating.

Time Test runs took between 15 and 20 minutes. Fig. 4.3a shows the walking speed corrected mean times (simple photographs: 17:15 min, static peephole: 15:33 min, dynamic peephole: 15:34 min). While the panorama-based prototypes outperform the variant based on simple photographs, the differences were statistically not significant. This is also true for the orientation times at waypoints. Overall, both the mean times and the median orientation times support the observations made.

Questionnaires Mean SUS scores (Fig. 4.3b) for all prototypes can be considered as good (simple photographs: 85.5, static peephole 88.5, dynamic peephole: 81). The mean UTAUT values of attitude are similar to the SUS scores. The values of anxiety are the same for all three prototypes. Statistical analysis did not confirm significance for the SUS scores or the UTAUT values.

Interview When confronted with all three prototypes, all users except one would prefer a panorama-based system. Statements on the preferred peephole interface were ambiguous. Some of the participants found the automatic orientation very useful, others said that the dynamic peephole produces a feeling of being other-directed. One user suggested a combination of maps and images.

4.1.4 Discussion

All participants using the panorama-based prototype were able to find the target location without losing their way. Users benefit from the contextual information, especially to verify their decisions. They were more self-confident and needed less time to orientate at waypoints. While there were no major differences in time and error between the static and the dynamic peephole, observations and interviews were mixed. However, none of the two outperformed the other. While the results of SUS and UTAUT were similar, they confirm the advantages of image-based approaches.

While the small number of errors indicates that the chosen route was too easy, we believe that it is appropriate for a realistic pedestrian navigation scenario. Both observations and interviews confirm our decision to limit the peephole interaction to horizontal rotation of the panoramic images. All participants held the device at a 45° pitch angle and no one claimed a vertical alignment.

4.1.5 Conclusion

In this section we presented an evaluation of static and dynamic peephole interaction with panoramic photographs and explored benefits of panoramas over simple photographs in a realistic pedestrian navigation scenario. While both peephole interfaces performed better than simple photographs, the user's feeling of being other-directed by the dynamic peephole is a serious problem. However, positive statements on the automatic orientation call for further research.

The publication An Evaluation of Peephole Interaction with Panoramic Photographs for Pedestrian Navigation in Part II provides details on the prototype, the study design, results and analysis, as well as a more detailed discussion.

4.2 Navigation with Combinations of Maps and Images

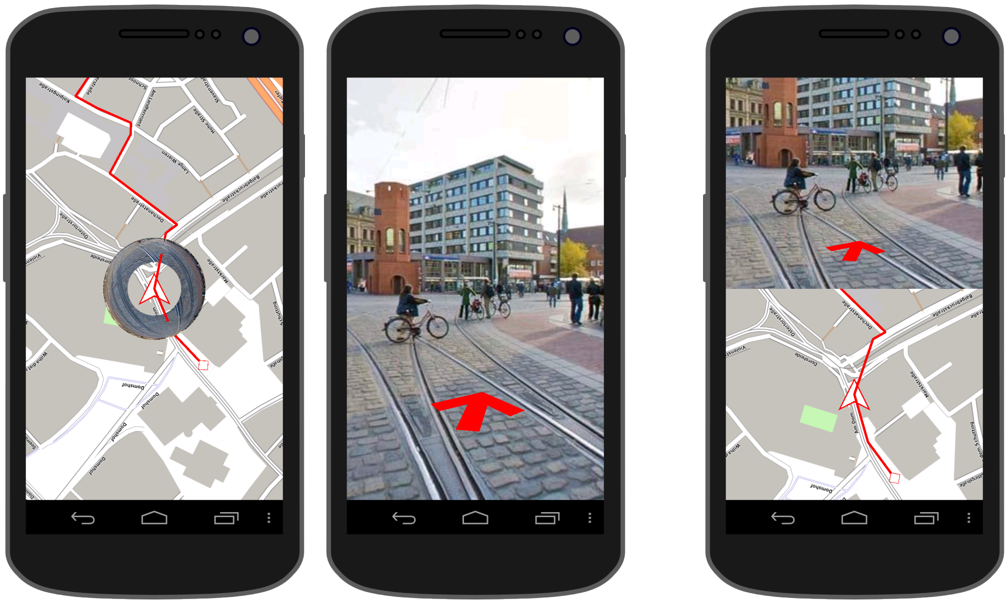
Dirk Wenig, Stefan Brending, Nina Runge, and Rainer Malaka (2014). "Using Split Screens to Combine Maps and Images for Pedestrian Navigation". In: *Journal of Location Based Services* 8.3, pp. 179–197. DOI: `10.1080/17489725.2014.977519`

Combining maps and images on mobile devices raises two main questions. First, two views have to be shown on one single screen. This can be handled in two ways; either by showing the map and the images alternately full-screen (time dimension, see Fig. 4.4a and Fig. 4.4b) or by showing both simultaneously using a split screen (spatial dimension, see Fig. 4.4c). While an alternating view helps the user to focus on one single media, it requires him to interact actively with the system to change its state. When using a split screen, on the other hand, the user has only to switch his gaze. However, the screen space for both media is smaller and the amount of information might overstrain the user. Second, a suitable level of interaction with the image content has to be found. While panoramic images offer contextual information, browsing the panorama increases the cognitive load. Simple photographs showing a limited and fixed area are focused on the most important part of the image and require less interaction and attention. However, they limit the field of view and do not allow the user to explore the surroundings.

In Using Split Screens to Combine Maps and Images for Pedestrian Navigation (Wenig et al., 2014), the goal was to investigate the advantages and drawbacks of manual switching and split screens for map-image combinations. First, touch-interaction and a physical gesture were compared to find out which approach is better suited for manual switching. Second, two split screen variants were evaluated against the manual interface; one employing panoramic images, the other using simple photographs.

4.2.1 Combining Maps and Images

Combining maps and images for a pedestrian navigation system is a challenge because the different requirements of the two media have to be taken into account. Regarding the user's position, an automatic translation of the map with the user in the center is standard. According to Seager and Fraser (2007) we decided to automatically rotate the map view based on the device's orientation with pointing direction up. Because of the map rotation, we decided on a *dynamic peephole* for the panoramic images to provide a clear and consistent interface. The panorama is vertically fixed and the interaction limited to horizontal rotation. For navigation instructions we decided to use a path in the map and arrows in the images.



(a) **(b)** **(c)**

Figure 4.4 The alternating map (a) and image (b) view and the split screen (c)

Alternating View The alternating view shows only one media at the same time in full-screen. This allows the user to focus on either the map or the image. We focus on manual switching: this allows the user to freely alternate at any time. Manual switching can be realized in different ways. While touch-interaction is the most obvious approach, a physical pitch gesture as proposed in Wenig and Malaka (2010) (Section 3.1 on page 19) might be an alternative. Therefore, in a pre-study we compared touch-based switching and the pitch gesture.

Split Screen In the split screen variant both media will be shown at the same time, but only on one half of the screen. In this approach, the user can see all available information at once and is not forced to interact with the device, but only to switch his gaze from one side of the display to the other.

Prototypes We developed four interaction prototypes implementing the two approaches of manual switching (touch and physical gesture) and the two split screen variants (panoramic images and simple photographs) for the *Google/Samsung Galaxy Nexus* smartphone. We used *GPS* to determine the user's position and built-in inertial sensors to estimate the mobile device's orientation. The map view shows pre-rendered OpenStreetMap data. A panoramic image is provided for each waypoint along a test route. Whenever the user approaches one of them he gets notified by vibration.

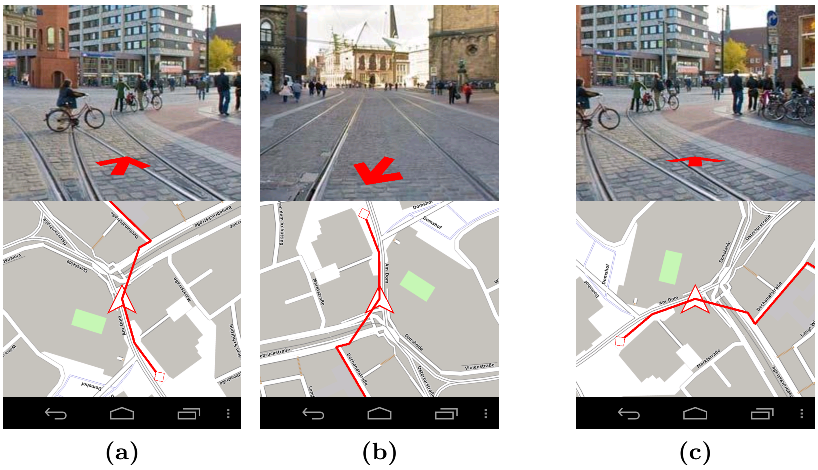

(a) (b) (c)

Figure 4.5 The split screen with a panorama in different orientations (a, b) and the split screen with simple photographs (c)

1) *Manual Switching using Touch:* The first manual switching variant relies on touch-interaction. It allows the user to switch between the full-screen map view and the full-screen image view at any time by tapping somewhere on the screen.

2) *Manual Switching using a Pitch Gesture:* The second manual prototype allows the user to switch between both views using a pitch gesture instead of touch. The threshold for switching is a pitch angle of 45°.

3) *Split Screen View with Panoramic Photographs:* The third prototype implements a panorama-based split screen (Fig. 4.5a, Fig. 4.5b depict the views presented to a user looking backwards)

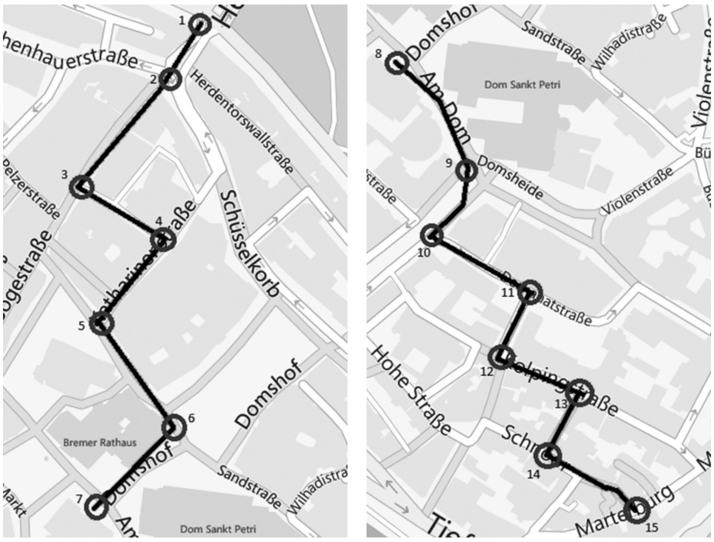
4) Split Screen View with simple Photographs: The fourth prototype realizes a split screen similar to the third prototype but shows a fixed panorama simulating simple photographs. Both the image and the arrow are locked pointing in walking direction (Fig. 4.5c) while the map automatically rotated.

4.2.2 Pre-Study Design

In a field study (within-subjects design, interfaces and routes Latin square counterbalanced) the two prototypes implementing manual switching were evaluated against each other to optimize the interface. The research question was:

(1) Is a touch-based interaction or a physical gesture better suited for switching between the views regarding performance and perceived usability?

Participants and Route We recruited 16 volunteers to test the two prototypes. The route starts outside the inner city and ends in the historic centre of Bremen (Germany). The route is 1,120 meters long and divided into two sections. Section A (Fig. 4.6a) is 550 meters long, section B (Fig. 4.6b) has a length of 570 meters.



(a) (b)

Figure 4.6 Test route section A (a) and section B (b)

Procedure The test persons were encouraged to think aloud and to ask questions if necessary. A supervisor followed the participants a few steps behind. We measured how long the test persons needed to complete the specific sections of the route and counted how often they left the route during the test run. The system logged how long the map view and the image view were used (*view shares*) and how often the participants switched between the two (*view switches*). We used the SUS (Brooke, 1996) questionnaire and two sets of four questions from the UTAUT (Venkatesh et al., 2003) to measure the attitude and effort expectancy towards the prototypes. In addition, noteworthy incidents were recorded in writing.

4.2.3 Pre-Study Results

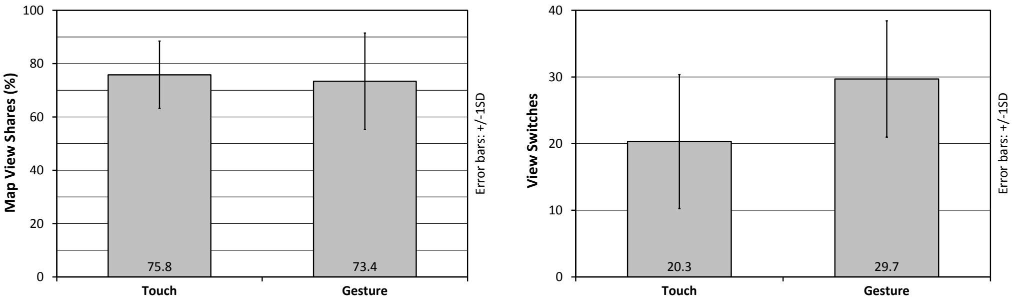
All subjects completed the navigation tasks and filled out the questionnaires.

Observation All the participants got along quickly with both user interfaces without needing to ask questions. The participants orientated themselves in different ways. Some made extensive use of the panoramic photographs, while others orientated themselves by the map. The arrow as a navigation aid was rated consistently positive.

Errors and Time A total number of six errors occurred: five errors with the touch-based switching and one error with the pitch gesture. The test runs on the different sections took between 5:35 min and 8:55 min. The mean time for the prototype were almost the same (touch 6:40 min, gesture: 6:46 min). Statistical analysis did not reveal significance.

Views Shares and Switches While the participants used the map view more often than the image view, the shares were almost equal for both prototypes. Fig. 4.7a shows the mean map view shares (touch: 75.8%, gesture: 73.4%). However, the mean number of the view switches differs between the two prototypes (see Fig. 4.7b). The participants switched more often when using the physical gesture (touch: 20.3, gesture: 29.7). Statistical analysis confirmed significance.

Questionnaires Mean SUS scores for both prototypes can be considered as good (touch 81.7, gesture: 91.4). Statistical analysis did not reveal any significance. The mean UTAUT values for both attitude (touch 90.0, gesture: 95.3) and effort expectancy show similar results (touch 75.4, gesture: 84.4). Statistical analysis did not confirm significance for either the attitude or the effort expectancy.



(a) (b)

Figure 4.7 Mean map view shares (a) and mean number of switches (b)

Interview In the interview the participants were asked to arrange the user interfaces in a ranked list. Eleven out of 16 test persons favored the pitch gesture. Most of the participants reasoned their choice with more simple and more intuitive interaction. Two of them criticized that the touch interface is not usable with gloves.

Conclusion While the measured time and the results of the questionnaires showed no significant differences between the prototypes, errors and interviews indicate advantages of the pitch gesture over touch-based interaction. Because of that, in the main study the method of manual switching with the pitch gesture was used.

4.2.4 Main Study Design

In a field study (within-subjects design, interfaces and routes Latin square counterbalanced) the two split screens and manual switching with a pitch gesture were evaluated against each other. The research questions were:

(1) Is one of the interaction concepts better suited for navigation relying on maps and images?

(2) Do panoramic photographs offer any benefits over simple photographs when combined with a map using a split screen?

Participants and Route We recruited 18 new volunteers to test the prototypes on three different route segments. Every volunteer received 10 Euros for expenses. The test route from the pre-study was supplemented with an additional section (Fig. 4.8).

Similar to the other two sections, it has a length of about 550 meters. It starts at the endpoint of section B and leads the user out of the historic centre.

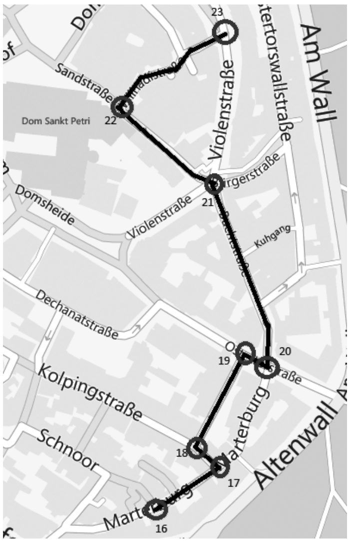


Figure 4.8 Test route section C

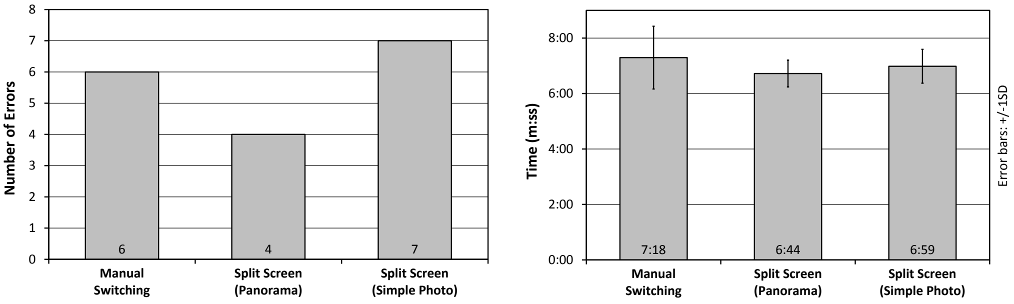
Procedure The procedure was the same as stated for the pre-study.

4.2.5 Main Study Results

Again, all participants completed the test runs.

Observation After the prototypes had been explained by the supervisor, all participants were able to use them. Nevertheless, the majority seemed to feel uncertain when using the split screen based on simple photographs.

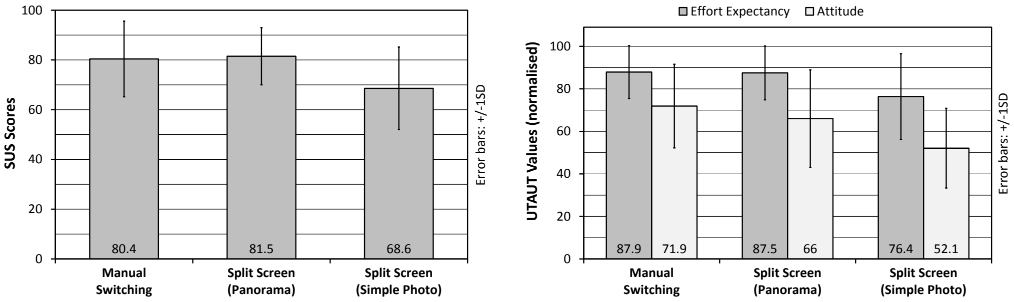
Errors and Time Overall, the subjects lost their way 17 times. Accumulated over all participants, six errors occurred with manual switching, four errors with the panorama-based split screen and seven with the split screen using simple photographs (see Fig. 4.9a). The test runs on the different sections took between 5:13 min and 9:12 min. Fig. 4.9b shows the mean times (manual switching: 7:18 min, panorama-based split screen 6:44 min, split screen using simple photos: 6:59 min). Statistical analysis did not reveal any significant differences.



(a) **(b)**

Figure 4.9 Total number of errors (a) and mean times (b)

Questionnaires Mean SUS scores (see Fig. 4.10a) can be considered as good for the manual switching and the panorama-based split screen, while the split screen using simple photographs fares worse (manual switching: 80.4, panorama-based split screen 81.5, split screen using simple photos: 68.6). Statistical analysis did not confirm any significant difference. The mean UTAUT values (see Fig. 4.10b) of effort expectancy show similar results (manual switching: 87.9, panorama-based split screen: 87.5, split screen using simple photos: 76.4). Again, statistical analysis did not confirm any significant difference. The mean UTAUT values of attitude are more clear (manual switching: 71.9, panorama-based split screen 66, split screen using simple photos: 52.1). Statistical analysis confirmed significant differences between manual switching and the split screen using simple photographs.



(a) **(b)**

Figure 4.10 Mean SUS scores (a) and mean UTAUT values (b)

Interview Eleven of 18 participants voted manual switching on the first place. Only one ranked this prototype on the last position, arguing that the system was too complex and the integration of the images was not good. Five of the test persons rated the panorama-based split screen best, only one would prefer the system using simple photographs. They explained their choice with the argument, that there was too much movement on the screen with the panorama-based split screen.

4.2.6 Discussion

All participants were able to use the manual switching prototype as well as both variants combining the map and the images in a split screen. The results of the study provide a two-fold picture. Statistical analysis did not reveal significant differences between the prototypes regarding time, error, the SUS scores and the UTAUT effort expectancy. Only the differences between manual switching and the split screen using simple photographs for the UTAUT attitude were statistically significant with better values for the manual prototype using panoramic images. However, overall the results and statistical analysis indicate slight advantages of the panorama-based systems regardless of whether the panoramic images were used in the manual switching or in the split screen variant. This correlates with the insights we gained in interviews. 17 of 18 participants ranked either the manual switching (using panoramic images) or the panorama-based split screen on first place. Our study confirms the results of Wenig et al. (2012) (Section 4.1 on page 24), showing that people benefit from the contextual information provided by panoramic images.

4.2.7 Conclusion

We presented an evaluation of different approaches to combine maps and panoramic photographs. In a pre-study we explored whether touch-based interaction or a physical gesture is better suited for manual switching between maps and images. Because the results indicate that a physical gesture is preferred by most of the users, we used this method for further investigations. In the main study we evaluated the system against two split screen variants: one based on panoramic images and one based on simple photographs. While we could not find one interface clearly outperforming the others, the results indicate advantages of panorama-based navigation systems for both cases of manual switching and split screens.

The publication Using Split Screens to Combine Maps and Images for Pedestrian Navigation in Part II provides details on the prototype, the study design, results and analysis as well as a more detailed discussion.

4.3 Map-based Navigation on Smartwatches

Dirk Wenig, Johannes Schöning, Brent Hecht, and Rainer Malaka (2015). "StripeMaps: Improving Map-based Pedestrian Navigation for Smartwatches". In: *Proceedings of the 17th International Conference on Human Computer Interaction with Mobile Devices & Services.* MobileHCI '15. ACM. DOI: `10.1145/2785830.2785862`

Before smartwatch map apps can meet their potential, important cartographic challenges must be addressed. These challenges arise from the very small screen size on smartwatches of typically 14 to 20 cm^2. This is only a tenth to a quarter of that of a typical smartphone screen with about 80 to 140 cm^2. Much of the art and science of reference map cartography – the type of cartography used in online and mobile maps (Slocum et al., 2005) – involves simplifying a large, complex world for display on a much smaller canvas (MacEachren, 2004). In general, the smaller the canvas, the harder the simplification, regardless of whether the canvas is digital or paper. Since smartwatch map apps are likely to be the smallest maps that have ever come into common use, existing simplification approaches may not work well and new cartographic techniques may need to be developed.

In StripeMaps: Improving Map-based Pedestrian Navigation for Smartwatches (Wenig et al., 2015) we introduce a novel cartographic approach for smartwatch maps targeted at pedestrian navigation. Within HCI, the problem of adapting interfaces originally developed for larger-screen displays to smaller devices is well-known and well-studied (Marcotte, 2011; Hwang et al., 2003; Siek et al., 2005; Zhang, 2007). One best practice that has emerged in modifying desktop websites for mobile devices is linearizing the design from a multi-column layout to a layout with a single column. Like desktop websites, maps extend in two dimensions, and the objective of StripeMaps is to adapt this linearization process to the cartography context. The specific approach taken by StripeMaps is motivated by a small family of traditional paper-based cartographic products used for long overland trips (e.g. via car or motorcycle). These products take a route which zigzags in two-dimensions and carves the route into segments such that each segment of the route can be rotated and displayed for printing on a piece of paper. Such route-customized booklets were used on road trips prior to GPS and smartphone navigation.

StripeMaps adapts this approach to linearize route maps into "stripes" (Fig. 4.11). These "stripes" can easily be browsed on a smartwatch by scrolling in only one direction (as one does with a well-designed mobile website). StripeMaps simplifies the

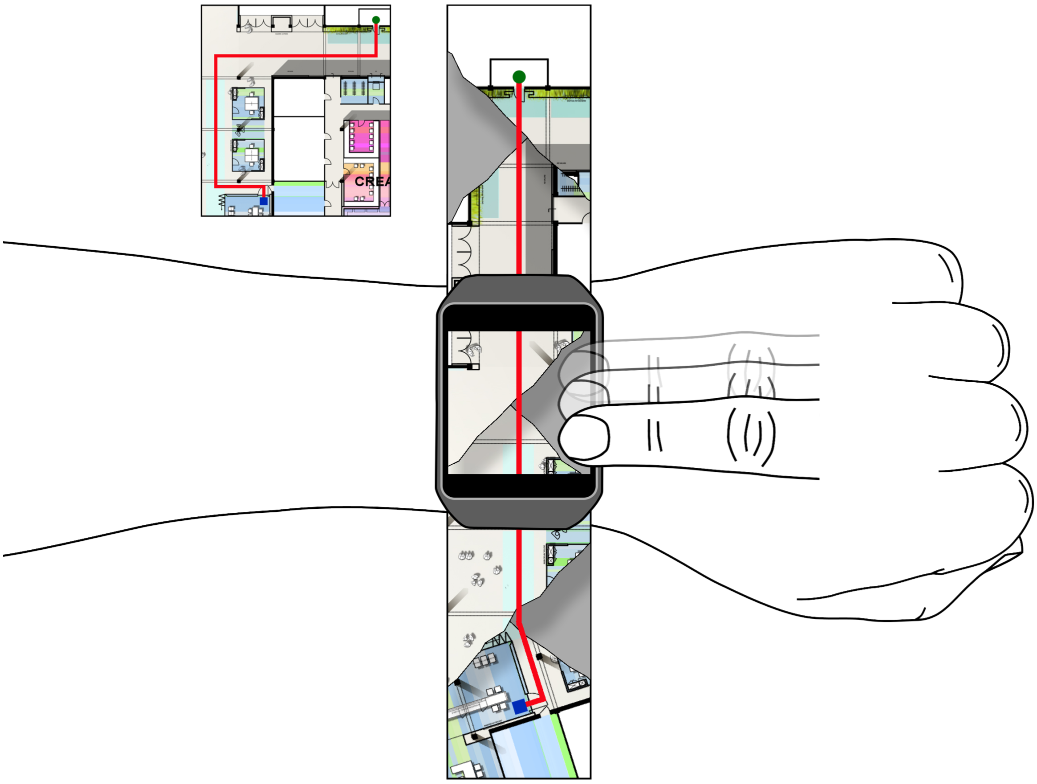


Figure 4.11 StripeMaps concept (original path on the 2D map shown in the mini-map in the upper left corner)

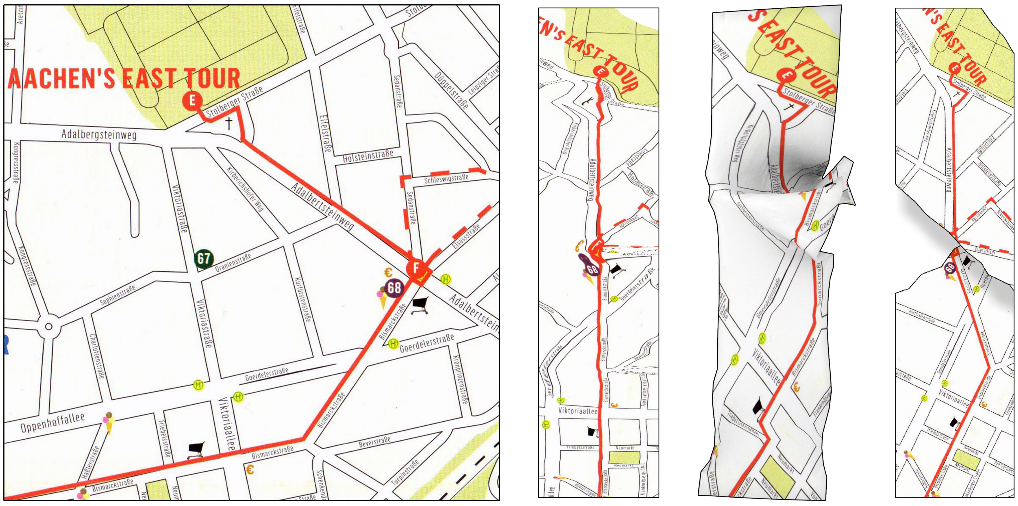
world into a single linear stripe, centered on the route of interest. We hypothesized that StripeMaps would be better for pedestrian navigation on smartwatches than traditional mobile map interfaces, which were originally designed for larger display devices and preserve both dimensions. At the same time, we also hypothesized that StripeMaps would have important pedestrian navigation advantages over text turn-by-turn directions which eliminate all spatial context entirely.

We performed two studies to test the utility and effectiveness of the StripeMaps smartwatch app for pedestrian navigation. The first study was focused on comparing the StripeMaps app against commonly used navigation techniques implemented on smartwatches in a controlled indoor environment. Specifically, we used turn-by-turn navigation and traditional mobile map navigation as baselines. The second study was designed to explore the use of the StripeMaps app "in the wild".

4.3.1 The StripeMaps Technique

The goal of the StripeMaps technique is to convert any 2D route map into a single, 1D stripe (as in Fig. 4.11). There are two major challenges involved in this process. The first involves selecting a visualization strategy for representing a 2D route in a straight line on a smartwatch. The second challenge involves executing that transformation on arbitrary 2D route maps.

Visualization Strategies A number of dimension reduction strategies are available in the cartography literature and practice. The most well-known come from map projections, in which the goal is to minimize high-cost distortion when representing the earth's three-dimensional shape on a two-dimensional paper or digital surface.



(a) (b) (c) (d)

Figure 4.12 Different visualization strategies for maps (a): route created by the transmogrification tool (b), simulation of a map printed on a piece of cloth (c) and map printed on paper and then cut and reassembled (d)

The first visualization strategy we tested for StripeMaps was to transform the area along a route using an adaptation of the transmogrification approach by Brosz et al. (2013). However, as can be seen in Fig. 4.12b, these transformations are very difficult to interpret because it is hard to identify the decision points. In addition labels and the environment at decision points can be heavily distorted.

The underlying idea of the second approach, inspired by the work of Sarkar et al. (1993), was that the map could be "virtually printed" on a deformable material (such as fabric or clay) and then deformed into a stripe. An example visualization can be seen in Fig. 4.12c. This approach resulted in less information loss along the way, but again the information density at decision points was very high.

The third design adapted the second approach, but instead of taking "fabric" or "clay", we used "paper". As analog maps are usually printed on paper, cutting a digital map into pieces and then rearranging the pieces into a stripe should be an easy to understand transformation model. Furthermore, as can be seen in Fig. 4.11 and Fig. 4.12d, it results in less information loss at decision points. A side effect is that the cuts provide excellent information on how to turn at these points. The cuts do not only show the rough direction but the exact turning angle.

We compared the visualization strategies with different maps on a smartphone and gathered feedback from different users. Option c was ranked best as it provides the best benefit between information loss and a transformation easy to understand.

StripeMaps Algorithm There are two main aspects for the transformation process: 1. *where* the cuts are performed and 2. *how* the cuts are performed. Cuts are not performed at every single waypoint because for zig-zag path segments, this might result in a shattered stripe. Cuts are only performed if not cutting would result in a path beyond the left and right boundary of the stripe. The way the cuts are performed is simple: the paper is virtually cut along the angle bisector between the previous path segment and the following one. Then, the resulting pieces are rotated around the waypoint itself to achieve a straight path.

4.3.2 The StripeMaps App

We have implemented the StripeMaps visualization and transformation approaches into our StripeMaps app for smartwatches. The StripeMaps app is targeted at the use case of pedestrian navigation, in particular indoor pedestrian navigation. In the current version of the StripeMaps, we have used the following as our motivating use case: when a StripeMaps user enters a building whose floor plan has been loaded into the app, s/he receives a notification on her/his smartphone that StripeMaps is available to help navigating through the building. After selecting a target location using the smartphone (which displays the floor plan and a list of rooms to aid this process), a StripeMap is generated and is pushed to the user's smartwatch for navigation including the geomagnetic orientation for all path segments (see subsection 4.3.3). The user then uses the StripeMap to get to her/his destination.

System Overview For the implementation, we used an *Android Wear* smartwatch *(Samsung Gear Live)*, an *Android* mobile device *(Google/LG Nexus 4)* and a server app (running on a *desktop PC*) based on *Java*. The communication between mobile device and smartwatch happens via Bluetooth, the communication between mobile device and server is based on TCP/IP so they are able to communicate over Wi-Fi and mobile network.

4.3.3 Design of Indoor Study

The first study was conducted in the main university building on the campus of a Western European university.

Participants We recruited 16 participants. All of them were unfamiliar with the university building, as they had just started their studies at the university the week of the experiment. None of our participants had used a smartwatch before.

Procedure The participants were introduced to the experiment and instructed to find four different offices and labs in the university building. The maps used in the study were already pre-loaded onto the smartwatch by the experimenter, so the participants did not need to use the companion smartphone app (e.g. to push the StripeMap to the smartwatch). The four navigation tasks had similar lengths and similar characteristics (e.g. # turns and complexity). All participants performed the test under all of the following conditions (within-subject design). The orders of the four conditions and of the routes were counterbalanced:

1) *Turn-by-turn navigation instructions (TBT):* The instructions for the turn-by-turn condition were created independently by three long-term members of the university community, who then worked as a group to iteratively merge their introductions together. They were instructed to use best practices in turn-by-turn navigation, e.g. by referencing landmarks rather than distances (May et al., 2003).

2) *2D Map (2D):* In the 2D Map condition, the participants could pan through a typical 2D map of the building with the highlighted route in red but were not allowed to zoom in/out. The map was on the same scale as in the SM and SM+O conditions, so the users could see the same amount of the map.

3) *StripeMap (SM):* In the StripeMap condition the participants used the app as described above.

4) StripeMap with orientation indicator (SM+O): In the StripeMap with orientation indicator condition, an orientation indicator was added to the StripeMaps app. It had two functions. First, using the smartwatch's built-in compass it shows the direction for the path segment the participant is currently looking at. Second, the app does not allow the user to scroll "down" the route as long as the participant had not turned in the correct direction.

(a) **(b)** **(c)** **(d)**

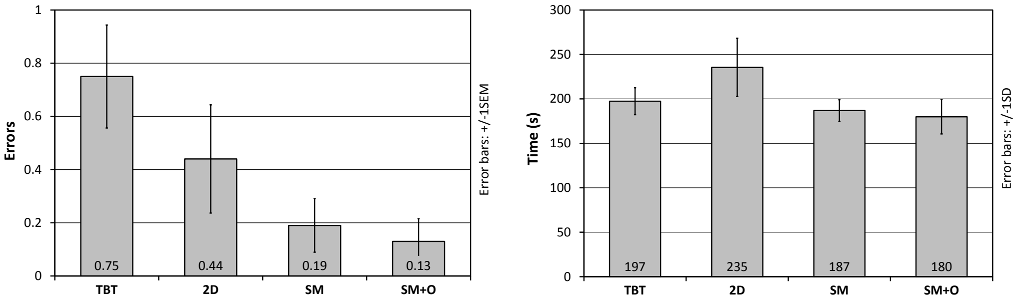
Figure 4.13 Four conditions of study 1: turn-by-turn-based navigation (a), a 2D map that can be panned (b), the StripeMaps app (c) and StripeMaps with orientation indicator (d)

As participants walked the route, an experimenter shadowed them and collected timing information and counted the number of navigation errors they made. An error was tallied when a participant took a wrong turn without noticing within five meters. Then, the participant was told of his/her error and sent in the correct direction. We used the SUS (Brooke, 1996) to measure the perceived usability and the NASA-TLX (Hart and Stavenland, 1988) to measure the perceived workload. Both questionnaires were filled out after each navigation task. Participants were encouraged to think aloud. Noteworthy incidents were recorded in writing. A semi-structured interview was conducted afterwards.

4.3.4 Results of Indoor Study

All participants were able to complete all the tasks. The participants took about 200 seconds per route on average and made an average of 0.38 errors per route.

Errors and Time Fig. 4.14 summarizes the performance results. The SM+O condition performed best with 180 seconds on average with a very low error rate of 0.13 (maximum of 1 error on each route). Just two of 16 participants took a wrong



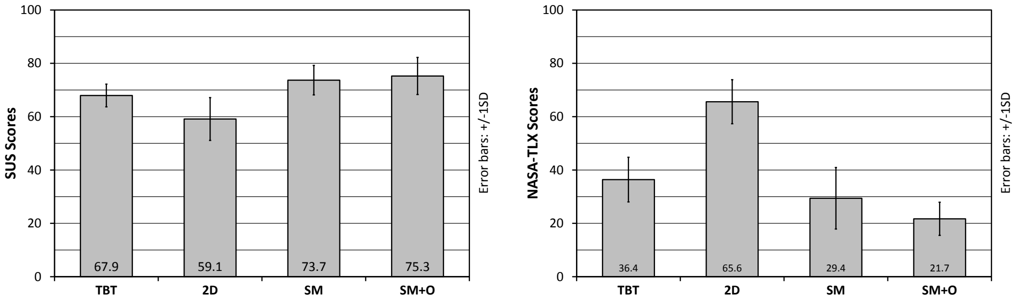
(a) (b)

Figure 4.14 Mean number of errors (a) and mean times (b)

turn. The second best was the SM condition with an average completion time of 187 seconds and an error rate of 0.19 (max 2 errors). In the TBT condition, participants took about 197 seconds on average, and made about 0.75 errors on average per route (maximum of 3 errors). The TBT condition resulted in the most errors. The participants took the most time with the 2D map condition (235 seconds on average and 0.44 errors). It is noteworthy that participants spent most of the additional time in the 2D condition switching between the interaction on the smartwatch and then navigating through the building.

For time, statistical analysis confirmed significant differences between TBT and the 2D condition, SM and the 2D condition, SM+O and TBT as well as SM+O and the 2D condition. Overall, with regard to time to complete a route, both StripeMaps variants outperform a 2D map. Moreover, StripeMaps with the orientation indicator is significantly better than turn-by-turn navigation instructions, making it the fastest of all conditions. Regarding errors, statistical analysis confirmed that SM+O resulted in significantly fewer errors than TBT. StripeMaps without an orientation indicator also resulted in fewer errors, but it was not significant. There were no significant differences between both StripeMap conditions and the 2D map.

Questionnaires Mean SUS scores (see Fig. 4.15a) can be considered as good for both StripeMap conditions (SM = 73.7 and SM+O = 75.3), followed by an average score of 67.9 for TBT and the 2D condition (59.1). Statistical analysis confirmed significance between all four conditions except between SM and SM+O: between TBT and the 2D condition, SM and the 2D condition, SM and TBT, SM+O and the 2D condition as well as between SM+O and TBT. Overall, regarding the perceived



(a) (b)

Figure 4.15 Mean SUS scores (a) and mean NASA-TLX overall values (b)

usability, the StripeMap concept in both variants outperforms both turn-by-turn navigation instructions and traditional 2D maps.

The mean overall values for the NASA-TLX (see Fig. 4.15b, normalized between 0 and 100) are low for both StripeMap conditions (SM = 29.4 and SM+O = 21.7), which means that the workload is also low. While this is also true for the average value of 36.4 for TBT, the workload for the 2D condition was high (65.6). Again, statistical analysis confirmed significant differences between TBT and the 2D condition, SM and 2D, SM+O and 2D as well as SM+O and TBT. That means that while SM achieved a low workload comparable to TBT although it shows a more complex visualization (map), SM+O even outperformed TBT.

Interview In the semi-structured interviews the use of the StripeMaps smartwatch app was perceived positively by all participants. They commented that the StripeMaps app "makes life so much easier" (P5) and "that it provides a good trade-off between clear instructions and a full a map" (P12). At the end of the test runs, we asked the participants to rank the interfaces. All participants favored one of the two StripeMap variants. Three of the 16 participants ranked SM first, while 13 ranked SM+O first. Those that did not rank SM+O first, ranked it second. All of the participants except one ranked the standard mobile map 2D condition last.

4.3.5 Design of Outdoor Study

To gain a more qualitative understanding of users' interaction with StripeMaps and to see how it is used "in the wild" rather than in a controlled environment, we conducted a second user study. The study took place in a mid-sized Western European city. During the year 2014, the city celebrated a major anniversary of the death of an important historical figure and former resident, drawing many tourists into the city. We drew our participants from this population of tourists.

We used the official tourist map of the city and turned the tours shown on the paper map into StripeMaps (using the SM condition from the first study). We preinstalled these StripeMaps on a smartwatch. We than approached randomly selected tourists close to different sights along the tours and asked if they would like to try out our research prototype.

Procedure Eight participants took part in the study. The study was conducted across two days in summer with good weather conditions. After the participants agreed to take part in the user study, we introduced them to the app. The experimenter then joined the participants while they were continuing their activity (visiting the city). After 20 minutes, we asked the participants to provide us feedback on the app and fill out a SUS questionnaire. This was followed by an informal interview with the participants.

4.3.6 Results of Outdoor Study

Overall, the StripeMap app received a SUS score of 79 on average. Participants offered positive qualitative feedback: P5 mentioned that “the main advantage of this thing is that I do not have to pull out the map or my mobile out of my pocket again and again. I would like to have this on my trip to Barcelona, as it makes me feel more secure” (referring to her worries about getting her smartphone stolen). She continued that “the map does not distract a lot, it is simple and nice – you can just scroll through. I can also imagine this as a map for my next marathon”. Several participants (P3, P6, P7, P8) commented that the app was also fun to use. P8 missed that the StripeMap app did not make use of the GPS, he said that “If you would add the blue GPS dot, than it would be perfect, but still this is great. GPS has still some problems in some cities. A simple modification would also be if the stripe scrolls automatically with your walking speed. Nevertheless this would work better than Google Maps shown on the Apple watch, this is cool!”

4.3.7 Discussion

Smartphones are not an ideal platform for pedestrian navigation systems. Weaknesses include the frequent need for two-handed interaction and having to take the device out of a purse or pocket in order to view a route and perform other tasks. This interaction overhead creates distractions, with pedestrians potentially overlooking risks of oncoming traffic or obstacles in their way. Smartglasses are the most unobtrusive interface and certainly solve some problems but while supporting always-visible navigation instructions, they lack direct forms of interaction and currently can incur some social costs (Hong, 2013).

Smartwatches are a compromise: they potentially incur fewer social costs, provide direct interaction and are always at hand. The problem, however, is that their screens are unprecedentedly small for interactive smart devices. In our studies, we have provided evidence that StripeMaps can help to overcome this obstacle in the use of smartwatches in pedestrian navigation. Specifically, we have shown that using StripeMaps results in faster route completion with fewer errors than other smartwatch cartographic approaches. StripeMaps also received positive qualitative feedback in our user studies, with participants expressing explicit enjoyment in the reduction in spatial complexity that was the goal of the StripeMaps approach.

While we compared StripeMaps against current smartwatch map approaches, we did not compare StripeMaps against the traditional “turn-by-turn”-style 3D display that is included as a feature in most smartphone map apps. Full-featured turn-by-turn displays are not yet available on smartwatches, and as such, StripeMaps’ performance relative to these displays is not known. However, turn-by-turn 3D displays require highly accurate position information, and this information is not available in indoor environments. StripeMaps does not require position information, making it suitable for indoor navigation, which is a critical use case for pedestrian navigation (e.g. campus buildings, malls, airports).

4.3.8 Conclusion

These results problematize some of the cartographic design choices of the first wave of smartwatches. Apple, for instance, currently uses traditional mobile map cartography in its Apple Watch map app. This is an approach that our results suggest will result in slower navigation times (for pedestrian navigation) and worse usability metrics than StripeMaps.

In summary, this paper makes the following contributions: We introduce StripeMaps, a new cartographic approach for smartwatch maps that results in improved pedestrian navigation relative to traditional mobile map cartography and turn-by-turn directions. We perform the first studies that compare smartwatch cartographic techniques. This sheds light not only on the advantages of StripeMaps, but also on the comparative pros and cons of existing cartographic approaches for smartwatch maps. Finally, this paper has provided evidence that linearization has benefits in cartography, just as it does in mobile web design.

The publication StripeMaps: Improving Map-based Pedestrian Navigation for Smartwatches in Part II provides details on the visualization approach, the transformation algorithm, results and analysis as well as a more detailed discussion.

Chapter 5

Virtual Exploration and Games

The research in the following chapter explores navigation in virtual worlds with a focus on virtual exploration and games on mobile devices. Furthermore, it presents a novel *physical locomotion* interface for virtual environments.

Maps and images complement each other not only for pedestrian navigation but also for virtual exploration. Combining both in a 3D virtual world requires interaction concepts for navigation in 3D space. For smartphones and tablets, due to the lack of input devices most of the interaction has to be realized on small sized touchscreens. The first of the following sections presents a software prototype for mobile devices combining well-known touch interaction techniques using a discrete and a continuous *pitch gesture*.

The second section adapts this idea for mobile games. Currently, mobile game controls are mostly based on touch interaction or physical gestures such as tilting the device. Both approaches often interfere with the player's view on the game world; by occluding parts of the screen, enforcing a limited view angle or fast shaky movements of the whole device. The section presents a novel control concept for mobile games integrating the pitch gesture and touch interaction. It uses a *different meaning of touch* depending on the device's orientation and a corresponding view in the virtual world. The result is a clean user interface with no distracting objects on the screen but enhanced interaction possibilities. In a user study, the concept was evaluated against a variant realizing the view switching by touch and against software buttons.

The third section investigates AR games on mobile devices. Augmenting the real world with virtual game elements allows gaming with a high level of immersion. To achieve high accuracy, a common solution for synchronizing the real world with the virtual world is to use fiducial markers that are tracked by the device's camera. Because the player has to keep the AR world in view at all times, controlling virtual characters in such games is more challenging than controls for pure VR games. The section presents and evaluates three control concepts for a mobile AR multiplayer fighting game: a virtual joystick, an absolute touch interface and continuous crosshair tracking.

The final section presents a novel *physical locomotion* interface for virtual environments. It suspends the user in a torso harness so that the feet just touch the ground. Low friction materials allow walking motions with ground contact similar to real walking, while maintaining the user in the same position. The section details the hardware and motion tracking setup and outlines the results of a first user study.

5.1 Exploring Combinations of Maps and Images

Dirk Wenig and Rainer Malaka (2011). “pitchMap: A Mobile Interaction Prototype for Exploring Combinations of Maps and Images”. In: *Proceedings of the 11th International Symposium on Smart Graphics.* Vol. 6815. Lecture Notes in Computer Science / SG ’11. Springer, pp. 188–189. DOI: `10.1007/978-3-642-22571-0\_23`

Mobile interaction concepts for navigation in 3D space are challenging. Especially modern smartphones often only offer few hardware buttons with fixed functions but no complex input devices such as trackpads. Therefore, most of the interaction has to be realized on small sized touchscreens. Furthermore, de facto standards for touchscreen interaction have been established. Map apps such as *Google Maps Mobile* translate the map when the user touches the screen. Panoramic image apps (e.g. *Google's Street View*) link touchscreen input to view rotation. *Google Earth* for mobiles combines both; it allows the user to switch between translation and rotation via a software button.

Following the idea of *spatially-aware displays* (Fitzmaurice, 1993) we suggested a *pitch gesture* for switching between the map view and the image view as an intuitive interaction technique in Wenig and Malaka (2010) (Section 3.1 on page 19). It implements a *peephole*-like positional mapping (Yee, 2003); it shows the map when the user holds the devices horizontally and the image content when the user holds it vertically. In pitchMap: A Mobile Interaction Prototype for Exploring Combinations of Maps and Images (Wenig and Malaka, 2011) we realized a different meaning of touch depending on the device's orientation (Fig. 5.1).

(a) **(b)**

Figure 5.1 Translation in map view (a) and rotation in image view (b)

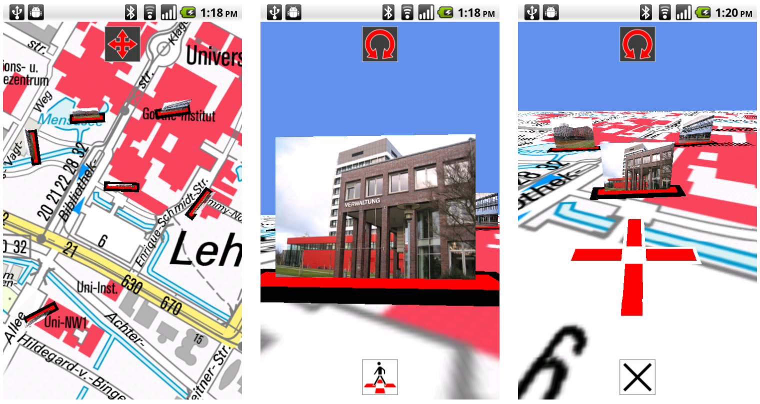
5.1.1 Prototype

We developed an interaction prototype for *Android* smartphones which are able to determine their orientation space (Fig. 5.2). The prototype shows geotagged photographs located on top of a map. When the user holds the device horizontally and the map is shown, touching the screen results in translation. When the user holds the device vertically and the image content is shown, touching the screen results in rotation. For switching between both views we implemented a discrete and continuous gesture. In a first informal test, users asked for a feature to change the position in the image mode. Therefore, we extended the functionality as follows: To move in the image view the user can touch a software button and drag an appearing crosshair to the target position (Fig. 5.2c).

5.1.2 Conclusion

Maps and images complement each other when combined in a 3D environment for virtual exploration. *pitchMap* is an interaction prototype combining well-known interaction techniques using a discrete and a continuous pitch gesture.

The publication pitchMap: A Mobile Interaction Prototype for Exploring Combinations of Maps and Images in Part II provides more details on the prototype.



(a) **(b)** **(c)**

Figure 5.2 Map view (a), image view (b) and target position (c)

5.1.3 Related Publications

- In Wenig and Malaka (2012) we extended the presented prototype with more complex interaction concepts (single touch using software buttons and multi touch gestures) allowing the user to translate and rotate in both views.
- In Wenig and Pollmann (2012) we investigated external input devices for 3D interaction with smartphones and tablets and present an interaction prototype combining the mobile device's touchscreen with a robot ball.

5.2 Indirect Sensor Control for Mobile Gaming

Daniel Böhrs, Dirk Wenig, and Rainer Malaka (2012). "Mobile Gaming with Indirect Sensor Control". In: *Proceedings of the 11th International Conference on Entertainment Computing.* Vol. 7522. Lecture Notes in Computer Science / ICEC 2012. Springer, pp. 441–444. DOI: `10.1007/978-3-642-33542-6\_48`

Dirk Wenig, Marc Herrlich, Daniel Böhrs, and Rainer Malaka (2013). "Mobile Games with Touch and Indirect Sensor Control". In: *Mensch & Computer Workshopband: Interaktive Vielfalt.* Workshop Entertainment Computing, Mensch & Computer 2013. Oldenbourg Verlag, pp. 261–266

Controls for smartphone and tablet games are mostly based on touch interaction, while some games of very specific genres (e.g. racing games) make use of the additional sensors available in modern devices such as the accelerometers. On their own, touch interfaces and physical gestures for mobile gaming can be problematic. Touch interaction is often restricted to a simple transfer of conventional hardware controls to software buttons. This results in difficult-to-use interfaces limiting the field of view of the player. Tilt-based interaction only allows simple controls and can be disturbing if the player turns the device to the side or shakes it while watching the screen.

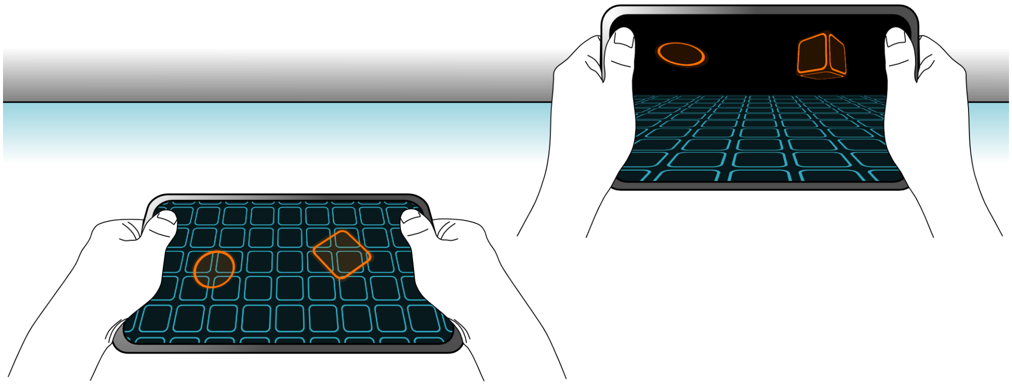


Figure 5.3 Pitch gesture for switching between different views on the game world

In Mobile Gaming with Indirect Sensor Control (Böhrs et al., 2012) and Mobile Games with Touch and Indirect Sensor Control (Wenig et al., 2013) we tackle these challenges and present a control concept combining a simple physical *pitch gesture* (Fig. 5.3) and *touch areas* (Fig. 5.4). While the touch area technique provides a button-less interface, the pitch gesture is used as an indirect control mechanism. As proposed in Wenig and Malaka (2011) (Section 5.1 on page 50), pitching the device allows the player to switch between a top-down view and a third-person view as well as to switch between two touch input modes: one for translation and one for rotation. The result is a clean interface with no objects on the screen but enhanced interaction possibilities.

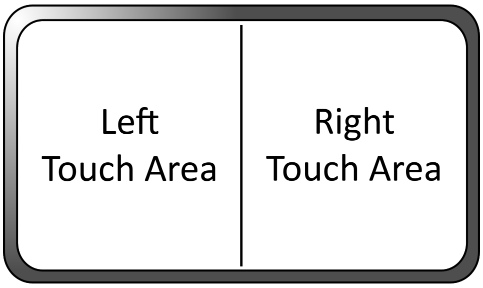


Figure 5.4 Touch areas

5.2.1 Game and Controls

(a) **(b)**

Figure 5.5 The game: top-down view for translation (a) and third person view for rotation (b)

Fig. 5.5 shows the concept transferred to a ball-through-labyrinth game for *Android* smartphones and tablets, which was employed as a testbed. The labyrinth is based on corridors which have to be passed. The ball moves forward continuously without the player's control and only stops at walls. The top-down view provides an overview but does not show objects in areas covered by tunnels. Only the third-person view allows the player to effectively navigate around these hidden objects. When the top-down view is shown, touch interaction results in rotation. In the third-person view, touch interaction results in translation. We implemented three different ways of switching between the two views: a physical pitch gesture, an additional touch area and traditional software buttons.

Physical gesture and touch areas The first concept is based on the pitch gesture. When the player holds the device horizontally, the top-down view is shown. S/he can switch to the third-person view by holding it in an upright position. The screen is vertically divided into two areas. Touching the left area triggers actions to the left while touching the right area triggers actions to the right. In the top-down view the action is a rotation. In the third-person view the action is a translation.

Touch areas The second concept is based on the first one but does not require physical interaction. Instead of switching the views by pitching, another touch area is added at the bottom of the screen (Fig. 5.6). This area is divided from the others by a thin gray line.

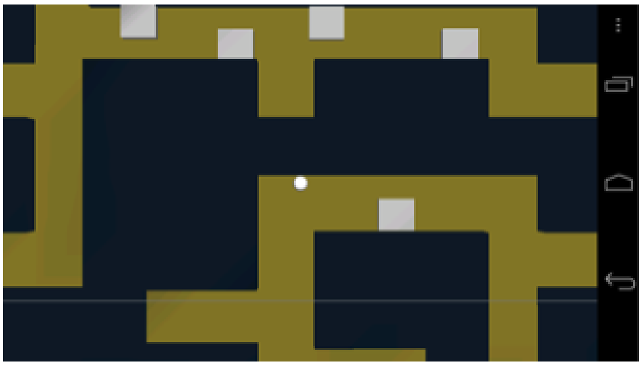


Figure 5.6 Touch area controls

Software buttons The third concept is based on traditional software buttons located at the bottom of the screen (see Fig. 5.7) for translation, rotation and switching the views (with both the left hand and the right hand). Because pre-tests suggested that rotating the view in the third-person view irritates users, the interaction was restricted: while players are allowed to translate in both views, rotation can only be triggered in the top-down view.

5.2.2 Evaluation

We conducted a user study to empirically compare the three different interaction concepts regarding subjective user experience with a focus on intuitive use, subjective preference and objective user performance. We wanted to test the following assumptions:

Figure 5.7 Software button controls

(1) Gesture-based interaction (even if restricted) is preferred to widget-based interaction (software buttons).

(2) Experience is more important than efficiency in the gaming context.

(3) Users are able to understand and successfully employ the view-switching techniques and the different control mappings for each view.

Setup The setup of the study followed a within-subjects design. The order of conditions was randomized. We chose a hybrid approach of on-site and online-based evaluation. On-site participants could choose between bringing their own smartphone or using one of our devices. Every interface condition was introduced by a short tutorial including screenshots explaining the goal of the game and the specific controls. The goal was to reach the exit of the maze as quickly as possible. Completion times, input events and the number of view changes were logged by the app for later analysis. After each condition, the app presented a digital version of the QUESI (Naumann and Hurtienne, 2010) questionnaire to collect subjective feedback concerning the usability. After they had played all three conditions, a semi-structured interview was conducted with all on-site participants. The online participants could choose to answer the interview questions in an online questionnaire.

Results Overall 22 users participated in the evaluation. Ten users participated on-site and twelve users online (only one answered the optional interview). Analysis of the log data revealed that completion times were similar across all conditions.

This is also true for the view-switching and view-specific interaction counts. In all conditions, the top-down view dominated both in terms of time spent in this view (overall approx. 83%) and in the number of interactions (overall approx. 86%). The results of the QUESI questionnaire differ in the conditions with touch areas rated highest, followed by tilt-touch-interaction and software buttons. The differences were statistically not significant. Five of the 11 participants who answered the interview questions rated the software buttons to be the most effective condition. Regarding fun, the participants almost unanimously voted for the tilt-touch interaction condition (9 of 11). Two participants found touch areas to be best in terms of fun. No participant voted for the software buttons in this category. When asked to choose the most limiting interface condition, most participants decided for the software buttons condition (7), four participants voted for the touch areas condition, and none for tilt-touch interaction.

Discussion With regard to our initial assumptions (assumption 3) it can be stated that users did indeed understand the view-switching mechanic and that they had no problems with changing the control mappings according to the view. The subjective usability rating shows that users preferred gesture-based interaction to widget-based interaction with software buttons (assumption 1). Although the touch areas lack any visual feedback, the concept was well received and rated best of all three interface conditions. Even though no objective differences regarding efficiency could be found, most users rated the software buttons to be the most effective. The tilt-touch interaction was rated to be the most fun and the least limiting condition. This does not fully confirm assumption 2 but indicates that experience may be more important than efficiency to users in the context of this study.

5.2.3 Conclusion

We presented a novel control concept for mobile games integrating touch-input and tilt-interaction using different input mappings depending on the device's orientation and a corresponding view in the virtual world. In a user study, we compared the concept to standard software buttons and pure touch-interaction. The results show that while all techniques are comparable regarding objective performance, i.e. game completion time, our concept increased the subjective user experience, which seems to be an important factor for designing mobile games.

The publications Mobile Gaming with Indirect Sensor Control and Mobile Games with Touch and Indirect Sensor Control in Part II provide more details on the interfaces and the results as well as a more detailed discussion.

5.3 Avatar Control in AR Games

Mareike Picklum et al. (2012). “Player Control in a Real-Time Mobile Augmented Reality Game”. In: *Proceedings of the 11th International Conference on Entertainment Computing*. Vol. 7522. Lecture Notes in Computer Science / ICEC 2012. Springer, pp. 393–396. DOI: `10.1007/978-3-642-33542-6\_36`

Frederic Pollmann, Dirk Wenig, Mareike Picklum, and Rainer Malaka (2013). “Evaluation of Interaction Methods for a Real-Time Augmented Reality Game”. In: *Proceedings of the 12th International Conference on Entertainment Computing*. Vol. 8215. Lecture Notes in Computer Science / ICEC 2013. Springer, pp. 120–125. DOI: `10.1007/978-3-642-41106-9\_14`

For AR on mobile devices there are approaches to use positioning systems and inertial sensors to synchronize the virtual elements with the real world. However, these approaches lack accuracy. Especially indoors, where positioning usually is not available, a common solution is to use special markers that are tracked by the mobile device’s camera. A drawback of this approach is that the marker has to be visible to the camera at all times. Otherwise, the synchronization of the virtual and real world gets lost. This poses additional constraints on the player and the way s/he may play the game.

In Player Control in a Real-Time Mobile Augmented Reality Game (Picklum et al., 2012) and Evaluation of Interaction Methods for a Real-Time Augmented Reality Game (Pollmann et al., 2013) we proposed and evaluated different interaction concepts to control the movement of an avatar in a real-time AR game (see Fig. 5.8). In the game, two players fight each other with an avatar in a fighting ring. Attacking is controlled by a software button on the screen. The goal was to find an input method that allows the players to quickly learn the game and to concentrate on playing and not moving the avatar. For the implementation, we used *Android* smartphones.

5.3.1 Controls

Controlling character movements in a game can be relative with respect to the position of the player, or absolute with respect to absolute coordinates of the world. For absolute control, the player sets the goal for the movement and the avatar moves by itself until the destination is reached or the action is interrupted by further user input. For continuous control, the input is read in each update cycle of the game,


(a) (b)

Figure 5.8 The running game (a) and two players fighting (b)

forcing the player to give continuous input until the desired position is reached. In Picklum et al. (2012) we initially proposed six different interaction concepts. Based on the feedback we gained, three of the six control concepts were evaluated:

Virtual joystick The first concept implements a touch-based virtual joystick that behaves in a similar way to its well-known hardware pendant. A circle is drawn on the touchscreen that symbolizes the movement range. The position of the player's finger inside the circle relative to its center defines the movement direction as well as the speed of the avatar.

Touchplane In the second concept, the player sets the target of the avatar by touching the screen. The avatar moves towards the corresponding position in the AR world until it is reached or the action is interrupted by setting a new target.

Crosshair The third concept uses the field of view of the mobile device's camera. A crosshair is drawn in the center of the display referencing a position in the AR world. The avatar continuously follows the crosshair. As a result, to control the movement of the avatar, the player has to move in the real world while keeping the marker tracked.

5.3.2 Evaluation

We conducted a user study (within-subjects design) to compare the different control concepts regarding the attitude towards the controls and subjective user experience, again with a focus on intuitive use. A total number of 43 players took part. We divided them into two groups. The first group (23 participants) played the game in a singleplayer mode; they had to defeat a computer-controlled enemy. The second group (20 participants) played the game in the multiplayer mode; they had to fight against other players. While participants of the singleplayer group had to fill out the QUESI (Naumann and Hurtienne, 2010) questionnaire, we conducted a semi-structured interview with participants of the multiplayer group. Additionally, they were asked to rank the control concepts regarding preferences. For both groups, observations were recorded in writing. The order of the controls was counterbalanced.

Questionnaire singleplayer In the questionnaire the virtual joystick achieved a mean score of 3.81, the touchplane a score of 4.02 and the crosshair a score of 3.37. Statistical analysis revealed significant differences between touchplane controls and the crosshair. Fig. 5.9 shows the mean overall scores and the results for the subscales. In all subscales except for the perceived effort of learning and the perceived error, the touchplane performed significant better than the joystick. This suggests that the crosshair concept is a new experience for the players that is easy to learn but not easy to master.

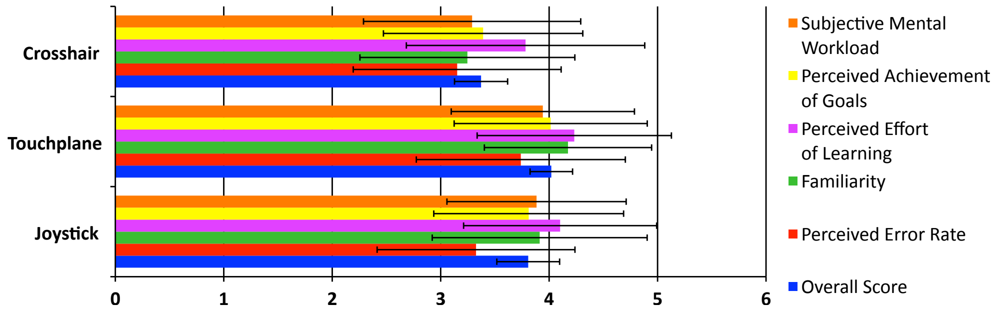


Figure 5.9 Mean QUESI scores including the subscales

Interview multiplayer When asked about the crosshair concept, 12 participants described it as unusual and complicated to use. Six persons found it interesting and innovative. Eleven initially expected to control the AR world instead of the avatar and first steered into the wrong direction. Two criticized a lack of precision while five criticized the sensitive reactions of the avatar to even slight camera movements. 15 test persons found the crosshair appropriate for the given game and preferred it over the touchplane and joystick input.

Twelve of the participants called the touchplane easy, beginner-friendly or intuitive. Eight of them did not rate it as suitable for games with a high degree of response from the player, because the player taps on the screen and then has to wait until the avatar reaches the position. Seven criticized an occlusion by the finger when tapping on the screen. For three of the participants it was difficult to control the rotation of the avatar, which is important for attacking. Only six test persons rated the touchplane as their favorite input method.

The joystick seemed to the most popular concept. 16 participants described it as easy to understand, simple and precise. Seven players mentioned the partial occlusion of the screen by the control elements as a disadvantage. Five participants were irritated by having to use both hands for the game; one for the attack button and one for the character control. Two participants suggested that the joystick should appear at the contact position of the finger on the screen. Four wished for haptic feedback when the finger leaves the outer edge of the joystick area. The overall personal ranking of the control concepts shows that the joystick is clearly preferred to the touchplane or the crosshair. 22 test subjects rated the joystick control as the most suitable input method for this kind of game.

In general, there was some criticism referring to the game itself and not the controls. Missing haptic feedback was criticized as well as a lack of control over the avatar's rotation. Several users had little or no experience with AR apps and needed to get used to it first. That made it difficult to differentiate between problems they had with the app and issues with the controls. Many participants asked for an input method based on physical control elements such as hardware buttons.

5.3.3 Conclusion

We evaluated three different interaction concepts for controlling a character in an AR game. We found a significant difference between the intuitive usability of the touchplane and the crosshair control concept. However, in the interviews the test persons did not prefer the touchplane method over the joystick. On the contrary, some players preferred the joystick because it was well known.

The publications Player Control in a Real-Time Mobile Augmented Reality Game and Evaluation of Interaction Methods for a Real-Time Augmented Reality Game provide details on the six initial control concepts and the interviews.

5.4 Physical Locomotion

Benjamin Walther-Franks, Dirk Wenig, Jan Smeddinck, and Rainer Malaka (2013c). “Suspended Walking: A Physical Locomotion Interface for Virtual Reality”. In: *Proceedings of the 12th International Conference on Entertainment Computing.* Vol. 8215. Lecture Notes in Computer Science / ICEC 2013. Springer, pp. 185–188. DOI: `10.1007/978-3-642-41106-9\_27`

Physical locomotion in virtual realities does increase the presence and can be used for applications requiring *natural full-body motions* from the user.

In the publication Suspended Walking: A Physical Locomotion Interface for Virtual Reality (Walther-Franks et al., 2013c) we propose *suspended walking*, a novel physical locomotion interface for virtual reality that enables more natural walking by suspending the user so that the feet just touch the ground (Fig. 5.10a and Fig. 5.10b). The user rests in a harness that is mounted to the ceiling or a frame, and stands upon a low friction surface wearing special slippers. This allows for a high degree of freedom of movement, most importantly a full walking motion, while still maintaining the sensation of touching the ground and remaining in the same location.

Suspended walking has advantages over existing physical locomotion techniques. It does not require large area tracking space and technology like actual walking techniques do. Unlike many devices simulating walking, the harness allows full freedom of movement for the legs, and does not suffer from device lag (unlike, for instance, a treadmill, which requires time to stop). It also enables turning motions and can be extended to support jumping.

5.4.1 Technique and Setup

The harness was originally developed to aid walking-impaired patients in therapy. It consists of straps for the lower torso and loops for the thighs, which are attached to a yoke above the head. It requires a suspension that should safely carry at least twice the maximum weight expected for users. We experimented with low friction materials for the floor and feet, wool slippers or socks and a PVC sheet provided good characteristics.

The suspension setup works with both vision-based as well as accelerometer sensing, and we experimented with both. Our goal was to match our suspension setup

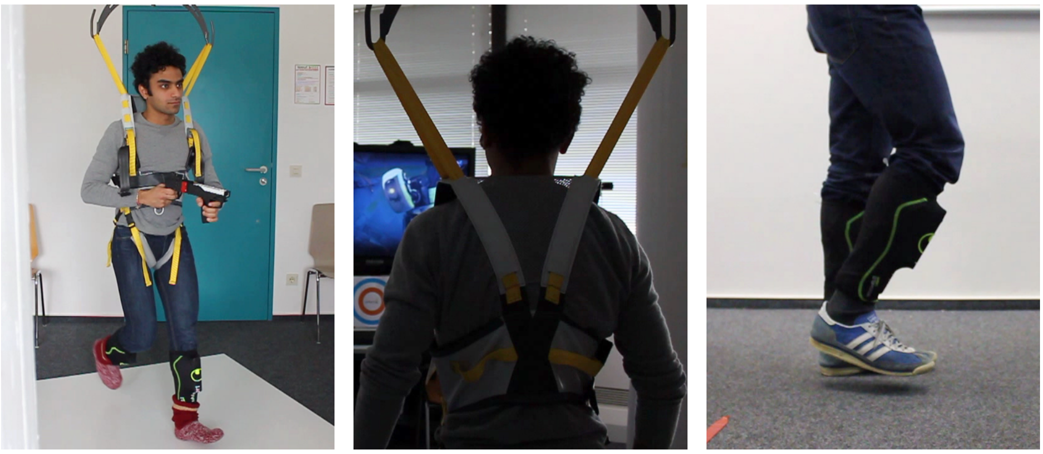

(a) (b) (c)

Figure 5.10 Suspended walking (a, b) and walking-in-place (c)

with state-of-the-art, low-latency walking recognition. Although skeleton recognition with the *Microsoft Kinect* worked well with the harness setup, we did not find it accurate enough for our purposes. We thus employed the signals of two 3-axis accelerometers (in the form of *Nintendo WiiMotes*), each attached to one lower leg of the user via shin guards.

Our walking detection is based on a state-of-the-art low-latency walk phase detection algorithm (Wendt et al., 2010), which we have already successfully used for a *walking-in-place (WIP)* technique (Walther-Franks et al., 2013b), see Fig. 5.10c. The recognition algorithm identifies the current step section of the leg movement using a series of optional conditions that need to be matched. The step frequency is transformed to walking speed using the heuristics of the *gait-understanding-driven (GUD)* WIP technique (Wendt et al., 2010). With small adjustments, we utilized the resulting predictions to implement a very low latency starting, stopping and walking speed detection. Although initially developed for WIP, this algorithm works with our suspended walking as well.

Suspended walking can be used with any kind of display setup. Since the user remains stationary, a heads-up solution is not required. In our working prototype, we achieved reasonable immersion with one large planar display. However, this only allows relative orientation gestures. In order to allow absolute orientation, a more immersive cave setup or heads-up display would be necessary.

5.4.2 Evaluation

To gather initial insights on our approach, we evaluated suspended walking in a user test against walking-in-place and the default keyboard and mouse setup. 18 test persons took part in the experiment. Each participant used each technique to play an exergame adaptation of the action game *Portal 2* (Walther-Franks et al., 2013b). The treatment consisted of an obstacle course specifically designed for the experiment with a level editor. While none of the participants found the suspension setup most comfortable, which was attributed to a not well fitting harness, six of them would use it again, and three rated it to be the most natural and intuitive user interface. However, none of the users found that suspended walking is easier to use than walking-in-place and the combination of keyboard and mouse.

5.4.3 Conclusion

We presented a novel physical navigation technique for virtual environments. Like walking-in-place and walking simulation devices, it does not require large-scale tracking spaces. It enables the user to perform a whole step cycle and approximates real haptical feedback from touching the ground, while providing more freedom of movement than simulation devices. Results of a qualitative study indicate its potential as a natural walking device, but also point out the importance of a correct harness adjustment.

The publication Suspended Walking: A Physical Locomotion Interface for Virtual Reality in Part II provides details on the algorithms and the setup.

5.4.4 Related Publications

- In Walther-Franks et al. (2013a) we present *Exercise My Game (XMG)*, a design framework for turning off-the-shelf action games into full-body motion exergames. It uses physical locomotion (suspended walking and WIP) as a control overlay.
- In Walther-Franks et al. (2013b) we illustrate the XMG framework with the example of turning the popular first-person action game *Portal 2* into the exergame *Sportal*
- In Herrlich et al. (2014) we discuss the health aspects of Sportal in the context of exergames and serious games.

Chapter 6

Discussion and Conclusion

The presented research aimed at taking advantage of motion input technology to design natural and intuitive interaction concepts for navigation in the real world and navigation in virtual worlds. First, a natural and intuitive motion-based interaction concept for pedestrian navigation and virtual exploration with mobile devices was presented (Chapter 3). It combines a pitch gesture with a peephole interface for interaction with combinations of maps and images on mobile devices (Section 3.1).

For navigation in the real world, the research focused on pedestrian navigation (Chapter 4). First, the benefits of panoramic photographs over simple photographs for image-based navigation were explored in a user study (Section 4.1). Furthermore, the study compared static and dynamic peephole interaction for panoramic images. Second, navigation based on maps and images was investigated (Section 4.2). In a user study, the pitch gesture to switch between the image view and the map view was compared against touch-based interaction. In another study, manual switching of views was evaluated vis à vis a split screen in two variants: one employing panoramic images and one using simple photographs. Finally, StripeMaps, a novel cartographic approach to display maps on smartwatches' small screens, was presented (Section 4.3). Two variants (one providing an orientation indicator) were evaluated against turn-by-turn navigation and traditional 2D maps.

For navigation in virtual worlds, the research focused on virtual exploration and games (Chapter 5). First, for the exploration of maps and images the pitch gesture was combined with a different meaning of touch depending on the device's orientation (Section 5.1). Second, the concept was brought to mobile games and evaluated against traditional software buttons in a labyrinth game (Section 5.2). Third, interaction concepts to control an avatar in an AR game were evaluated (Section 5.3). Finally, navigation in virtual worlds beyond mobile devices was explored by developing an interface for physical locomotion in virtual environments (Section 5.4).

6.1 Contributions

In addition to the particular contributions in the sections, the presented research makes five contributions based on the five hypotheses introduced in Chapter 1. First, the performed user studies shed light on the advantages and drawbacks of *natural and intuitive motion-based interaction* (H_1) for navigation in the real world and navigation in virtual worlds. Second, the research highlights the benefits of *contextual information* (H_2) provided by panoramic photographs for image-based pedestrian navigation. Third, it introduces a *novel cartographic approach for small screens* (H_3) improving map-based navigation on smartwatches. Fourth, the research presents an interaction concept based on a *different meaning of touch* (H_4) depending on the mobile device's orientation. Fifth, the user studies provide insights on the comparative *importance of user experience and subjective efficiency* (H_5) in the context of gaming.

6.1.1 Natural and Intuitive Motion-based Interaction

Natural and intuitive interaction concepts for both navigation in the real world and navigation in virtual worlds have to be carefully designed; motion-based approaches do not necessarily lead to better interfaces. While in the first study on navigation with maps and images most of the participants favored the pitch gesture over touch-based interaction because it was intuitive and simple, feedback on the dynamic peephole interface in the study on panorama-based navigation was ambiguous. Most of the participants were irritated that they had to rotate themselves for orientating in the panorama and some of them criticized a feeling of being other-directed. They preferred the static peephole with touch-based interaction. This is in line with the insights gained in the study on avatar control in AR games. The joystick was the most popular concept and preferred over the motion-based crosshair approach because it was well-known, simple and precise. Overall, for both navigation in the real world and navigation in virtual worlds the most important requirement for user interfaces is that they are easy-to-use and effective. Additionally, the interfaces are very much dependent on the point in the *Navigation Continuum*.

Conclusion Navigation in the real world and navigation in virtual worlds can both benefit from natural and intuitive interaction concepts based on the user's motions. However, each and every single user interface has to be carefully designed and evaluated with users. The often ambiguous feedback in the studies suggests to allow the user to switch between different interaction techniques.

6.1.2 Contextual Information of Panoramic Images

For pedestrian navigation, the presented research demonstrated the benefits of additional contextual information provided by panoramic images. In the study on panoramic photographs, the participants used the panoramic view to verify their decisions. The results were confirmed in the second study on navigation with maps and images. It also indicates advantages of panorama-based systems, for both the manual switching and the split screen variant.

When using simple photographs, the participants often searched for landmarks which were not pictured on the images. They also seemed to recheck the waypoints more often while walking. When using a panorama-based system, the participants often looked around in the panorama to identify landmarks before deciding where to go. In addition, they took the opportunity to verify their decision before proceeding and were more self-confident. This is in line with the results of May et al. (2003), who have shown that the identification of prominent landmarks helps to maintain the user's confidence that s/he is following the correct route and the navigation aid is working correctly.

All image-based navigation systems presented in this research used arrows to provide route information. For panoramic images, an advantage of arrows is that they provide clear information on where to go, even when the user is looking to the side or backwards in the panorama. However, for simple photographs, Walther-Franks and Malaka (2008) have found out that people prefer path visualizations over arrows. Therefore, future work should investigate alternative approaches to augment panoramic photographs with navigation instructions.

A problem of both turn-by-turn navigation and pure image-based navigation is the lack of information between waypoints. While maps do continuously provide route information, turn-by-turn and image-based navigation are limited to discrete instructions. This is especially a problem if positioning is not available or not accurate enough. A pedestrian navigation system relying only on images would probably require a very high number of panoramic photographs with only a few meters in-between in order to perform similar to maps or better than maps. Video-based navigation might be an alternative.

Conclusion Pedestrians benefit from contextual information provided by maps or panoramic images when navigating. Image-based navigation systems should not rely on simple photographs but on panoramic images. As long as there is a lack of information between waypoints, and positioning is not accurate enough or not available, navigation systems should provide a map view.

6.1.3 Novel Cartographic Approach for Small Screens

The StripeMaps approach clearly improved map-based pedestrian navigation on smartwatches. The user studies show that cutting a digital map into pieces and then rearranging the pieces into a stripe is an easy-to-understand transformation model and that the cuts provide excellent information on how to turn at decision points. This allowed StripeMaps to outperform both traditional mobile map interfaces and turn-by-turn directions on smartwatches. Using StripeMaps resulted in faster route completion with fewer errors. It also received positive qualitative feedback; the participants especially liked the reduction in spatial complexity. While StripeMaps does not require position information – making it suitable for indoor navigation – future work should investigate outdoor navigation including positioning.

Conclusion Novel cartographic approaches for small screens can improve map-based navigation on smartwatches relative to traditional mobile map cartography and turn-by-turn directions. Especially for navigation, it is important that the visualization is easy to understand. Therefore, natural approaches should be used.

6.1.4 Different Meaning of Touch

In the study on indirect sensor control for mobile games, all the participants understood the different meaning of touch. This is true for the pitch gesture as well as for the additional touch area. They did not have any problems with switching between different input mappings. This does not only allow to combine well-known interaction techniques, but also to realize more complex input without widgets on the screen. While the presented research combined two different touch modes with a corresponding view, future research should investigate a different meaning of touch without specific views. Additionally, different touch modes should be explored on other types of devices. Because the screens of smartwatches are much smaller than smartphones' screen, interaction concepts are more challenging. While on the practitioner side of things, there are approaches to use additional hardware buttons (e.g. the *digital crown* integrated in the *Apple Watch*), researchers have investigated expanding the input expressivity of smartwatches with mechanical pan, twist, tilt and click (Xiao et al., 2014). A different meaning of touch might be an alternative.

Conclusion Users do understand and are able to employ interfaces based on a different meaning of touch depending on the mobile device's orientation. However, this is also true for other approaches for switching between input mappings.

6.1.5 Importance of User Experience and Subjective Efficiency

The findings on the importance of user experience and subjective efficiency in the context of gaming are ambiguous. On the one hand, in the study on indirect sensor control for mobile games most users rated the software buttons to be the most effective while the tilt-touch interaction was rated to be the most fun and the least limiting condition. The results of the QUESI questionnaire differ in the conditions with touch areas rated highest, followed by tilt-touch-interaction and software buttons. This indicates that experience may be more important than efficiency to the players in the context of gaming. On the other hand, in the study on AR player control, the touchplane condition was rated highest in the QUESI questionnaire, followed by the joystick condition and the crosshair. However, in the interviews the test persons did not prefer the touchplane over the joystick. Quite the contrary: some players preferred the joystick because it was well known. A reason for the difference in the results might be the number of on-screen control elements. While in the first study, the software button interface required six control elements, the joystick in the second study followed the guidelines of Salo et al. (2012), who state that minimizing the number of on-screen control elements is very important.

Conclusion In the context of gaming, user experience is not necessarily more important than subjective efficiency. Therefore, interaction concepts for mobile games should also give the impression of being effective.

6.2 Evaluating Outdoor Pedestrian Navigation

Evaluating outdoor pedestrian navigation systems in the field is challenging. This is especially true for navigation involving positioning systems. In contrast to car navigation, pedestrian navigation systems require more accurate positioning. While for cars on lanes the difference of a few meters between the calculated position and the real position usually does not matter, for pedestrians such differences can be crucial and lead to navigation errors. This is a problem especially in urban areas as high buildings cause weak GPS signals. On the one hand, inaccurate positioning does influence the studied system and its usability. On the other hand, much more accurate and much more reliable positioning systems are not expected for the near future and navigation systems have to deal with such problems. Therefore, in the studies on navigation based on maps and images, a situation of GPS signal loss was forced by passing a shopping arcade. All positioning problems – the forced ones and the unwanted ones – have to be taken into account for the study design.

While a within-subjects design with counterbalanced interfaces and route sections is essential, also sufficient route segments where GPS works well have to be integrated. Furthermore, after the study, positioning logs should be analyzed.

Another serious problem with evaluating pedestrian navigation systems in a realistic scenario are the potentially dangerous situations for participants, which actually occurred in all the three outdoor studies. Before the test runs the participants were told that it is the system which is being tested and not the person. However, the majority of them tried hard to perform as well as possible. This is a problem, especially because the participants are navigating with a system which they have never used before. In the studies, most of them hold the device in their hands all along and looked at the screen every few seconds. The focus of attention was on the system, and this distracted them from the environment and the task of walking. As a consequence, from time to time some of the participants overlooked other pedestrians or cyclists. One of them even disregarded a red traffic light, another one overlooked a tram. While both could be stopped by the supervisor, in future studies such dangerous situations have to be absolutely avoided. If necessary, even at the cost of dispensing with a realistic navigation scenario.

6.3 Navigation Interfaces for VR Headsets

Currently, many companies are developing VR headsets (e.g. the *Oculust Rift*) for the mass market. They require novel physical locomotion interfaces for navigation in virtual worlds which allow the user to walk long distances, e.g. for first-person shooters, probably the most eagerly awaited game genre for VR headsets. While there are approaches to use treadmills or spheres (Medina et al., 2008), this work proposed suspended walking. Because the user rests in a harness that is mounted to the ceiling or a frame, suspended walking allows a high degree of freedom of movement. Future work should not only investigate suspended walking in combination with VR headsets, it should also explore additional motion actions such as jumping, crouching or combat to allow more natural navigation in virtual realities.

6.4 Future of Pedestrian Navigation

Several studies have shown advantages of image-based approaches for pedestrian navigation. However, creating and updating the image content is still a problem due to costs and, at least in Germany, also because of privacy issues. Services for panoramic images such as Google's Street View are focused on streets; particularly those areas important for pedestrians are missing. Because the images are primarily taken from cars, usually there is an offset between the sidewalk and the panoramic image's location. Additionally, inner cities often change. In the studies on pedestrian navigation the participants criticized that the panoramic images are out of date. Databases covering all areas for pedestrian navigation with up-to-date images are not expected for the near future. AR using live images, e.g. taken with the device's camera, might be a solution but requires highly accurate positioning. Outdoors this is still a problem, especially in urban areas, while indoor positioning is usually not available at all.

As long as these problems are not solved, pedestrian navigation systems should not only rely on images but also on maps to provide route information when images are not available. While the present dissertation investigated two approaches – an alternative full screen view and a split screen – to combine maps and images, these approaches were focused on mobile devices. In the future, wearable devices such as smartwatches or head-mounted displays are expected to play an important role in pedestrian navigation. Therefore, future work should aim at improving map-based navigation on wearables (StripeMaps is one approach doing so) and at bringing image-based navigation as well as combinations of maps and images to such wearables.

Part II

Publications

Chapter 7

Included Publications

While Part I summarizes the research in the context of navigation in the real world and navigation in virtual worlds, this chapter quotes the original research the summary is based on.

- Dirk Wenig and Rainer Malaka (2010). “Interaction with Combinations of Maps and Images for Pedestrian Navigation and Virtual Exploration”. In: *Proceedings of the 12th International Conference on Human Computer Interaction with Mobile Devices & Services*. MobileHCI ’10. ACM, pp. 377–378. DOI: `10.1145/1851600.1851673` (Section 3.1 on page 19)
    - **My part:** I contributed the idea and the concept and developed the prototype.
- Dirk Wenig, Tim Nulpa, Rainer Malaka, and Michael Lawo (2012). “An Evaluation of Peephole Interaction with Panoramic Photographs for Pedestrian Navigation”. In: *Proceedings of the Young Researchers Forum on Geographic Information Science*. Vol. 44. ifgiPrints / GI Zeitgeist 2012. Institut für Geoinformatik, Westfälische Wilhelms-Universität Münster. Akademische Verlagsgesellschaft AKA GmbH, pp. 23–32 (Section 4.1 on page 24)
    - **My part:** I developed the software framework the prototypes are based on, contributed the idea and designed the study, which was conducted by Tim Nulpa for his ‘Diplom’ thesis “Panoramafotografien für bildbasierte mobile Navigation (Panoramic Photographs for Image-based mobile Navigation)”. I supervised the thesis and, together with Tim Nulpa, analyzed the results.
- Dirk Wenig, Stefan Brending, Nina Runge, and Rainer Malaka (2014). “Using Split Screens to Combine Maps and Images for Pedestrian Navigation”. In: *Journal of Location Based Services* 8.3, pp. 179–197. DOI: `10.1080/17489725.2014.977519` (Section 4.2 on page 29)

  - **My part:** I developed the software framework the prototypes are based on, contributed the idea and designed the study, which was conducted by Stefan Brending for his 'Diplom' thesis "Evaluation von Fußgängernavigationssystemen mit kombinierter Panorama- und Kartenansicht (Evaluation of Pedestrian Navigation Systems with combined Panorama and Map View)". I supervised the thesis and, together with Stefan Brending, analyzed the results.

- Dirk Wenig, Johannes Schöning, Brent Hecht, and Rainer Malaka (2015). "StripeMaps: Improving Map-based Pedestrian Navigation for Smartwatches". In: *Proceedings of the 17th International Conference on Human Computer Interaction with Mobile Devices & Services.* MobileHCI '15. ACM. DOI: `10.1145/2785830.2785862` (Section 4.3 on page 38)
  - **My part:** The publication is a result of a research stay at the Expertise centre for Digital Media (EDM) at Hasselt University. Together with Johannes Schöning, I developed idea, concept and algorithm. Additionally, I developed the smartwatch/smartphone app including the baseline conditions and, again together with Johannes Schöning, designed as well as prepared the study and analyzed the results.

- Dirk Wenig and Rainer Malaka (2011). "pitchMap: A Mobile Interaction Prototype for Exploring Combinations of Maps and Images". In: *Proceedings of the 11th International Symposium on Smart Graphics.* Vol. 6815. Lecture Notes in Computer Science / SG '11. Springer, pp. 188–189. DOI: `10.1007/978-3-642-22571-0\_23` (Section 5.1 on page 50)
  - **My part:** I contributed the idea and the concept and developed the prototype.

- Daniel Böhrs, Dirk Wenig, and Rainer Malaka (2012). "Mobile Gaming with Indirect Sensor Control". In: *Proceedings of the 11th International Conference on Entertainment Computing.* Vol. 7522. Lecture Notes in Computer Science / ICEC 2012. Springer, pp. 441–444. DOI: `10.1007/978-3-642-33542-6\_48` (Section 5.2 on page 52)
  - **My part:** I contributed the idea. The prototypes were developed by Daniel Böhrs for his Bachelor thesis "Mobile Spiele mit Touch- und indirekter Sensor-Steuerung (Mobile Games with Touch and indirect Sensor Control)". I supervised the thesis and, together with Daniel Böhrs, I developed the control concepts and designed the game.

- Dirk Wenig, Marc Herrlich, Daniel Böhrs, and Rainer Malaka (2013). "Mobile Games with Touch and Indirect Sensor Control". In: *Mensch & Computer Workshopband: Interaktive Vielfalt.* Workshop Entertainment Computing, Mensch & Computer 2013. Oldenbourg Verlag, pp. 261–266 (Section 5.2 on page 52)
    - **My part:** The study is also a result of the supervised thesis named above. Together with Daniel Böhrs, I designed the study and analyzed the results.
- Mareike Picklum et al. (2012). "Player Control in a Real-Time Mobile Augmented Reality Game". In: *Proceedings of the 11th International Conference on Entertainment Computing.* Vol. 7522. Lecture Notes in Computer Science / ICEC 2012. Springer, pp. 393–396. DOI: `10.1007/978-3-642-33542-6\_36` (Section 5.3 on page 58)
    - **My part:** The publication is a result of a bachelor student project ("Mobile Virtuelle Welten (Mobile Virtual Worlds)") I supervised together with my colleague Frederic Pollmann. Together with the students, we formed the idea and controls concepts and developed the game.
- Frederic Pollmann, Dirk Wenig, Mareike Picklum, and Rainer Malaka (2013). "Evaluation of Interaction Methods for a Real-Time Augmented Reality Game". In: *Proceedings of the 12th International Conference on Entertainment Computing.* Vol. 8215. Lecture Notes in Computer Science / ICEC 2013. Springer, pp. 120–125. DOI: `10.1007/978-3-642-41106-9\_14` (Section 5.3 on page 58)
    - **My part:** The publication is a result of a bachelor thesis ("Steuerung eines Charakters in Echtzeit-Augmented Reality Spielen (Player Control in Real-Time Augmented Reality Games)" by Mareike Picklum) I supervised together with my colleague Frederic Pollmann. The thesis is based on the student project named above. Together with Frederic Pollmann and Mareike Picklum, I designed the study and analyzed the results.
- Benjamin Walther-Franks, Dirk Wenig, Jan Smeddinck, and Rainer Malaka (2013c). "Suspended Walking: A Physical Locomotion Interface for Virtual Reality". In: *Proceedings of the 12th International Conference on Entertainment Computing.* Vol. 8215. Lecture Notes in Computer Science / ICEC 2013. Springer, pp. 185–188. DOI: `10.1007/978-3-642-41106-9\_27` (Section 5.4 on page 62)
    - **My part:** The publication is a result of a master student project ("Sportal") I supervised together with my colleagues Benjamin Walter-Franks

and Jan Smeddinck. Together with the students, we formed the idea and interface concept and supported them in developing the prototype and conducting the study.

Chapter 8

Other Publications

Additionally, I was involved in the following scientific publications (in chronological order):

- Benjamin Walther-Franks, Dirk Wenig, Rainer Malaka, and Barbara Grüter (2009). "An Evaluation of Authoring Interfaces for Image-based Navigation". In: *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices & Services*. MobileHCI '09. ACM. DOI: 10.1145/1613858.1613930
- Hidir Aras, Sebastian Feige, Rainer Malaka, Benjamin Walther-Franks, and Dirk Wenig (2009). "Mobile Digital Media: Challenges and Opportunities". In: *it - Information Technology* 51.6, pp. 329–335. DOI: 10.1524/itit.2009.0559
- Sebastian Feige, Dirk Wenig, Christoph Pantel, and Rainer Malaka (2010). "Image-based Cycle Route Generation on Mobile Devices". In: *Proceedings of the 12th International Conference on Human Computer Interaction with Mobile Devices & Services*. MobileHCI '10. ACM, pp. 369–370. DOI: 10.1145/1851600.1851669
- Dirk Wenig and Frederic Pollmann (2012). "Externe Eingabegeräte für mobile 3D-Interaktion". In: *Mensch & Computer Workshopband: interaktiv informiert - allgegenwärtig und allumfassend!?* Workshop Be-greifbare Interaktion, Mensch & Computer 2012. Oldenbourg Verlag, pp. 173–176
- Dirk Wenig and Rainer Malaka (2012). "Mobile 3D-Interaktion zur virtuellen Exploration realer Umgebungen". In: *Mensch & Computer Workshopband: interaktiv informiert - allgegenwärtig und allumfassend!?* inter|aktion - Demosession, Mensch & Computer 2012. Oldenbourg Verlag, pp. 513–516
- Robert Hermann, Marc Herrlich, Dirk Wenig, Jan Smeddinck, and Rainer Malaka (2013). "Strong and Loose Cooperation in Exergames for Older Adults

with Parkinson's Disease". In: *Mensch & Computer Workshopband: Interaktive Vielfalt.* Workshop Entertainment Computing, Mensch & Computer 2013. Oldenbourg Verlag, pp. 249–254

- Benjamin Walther-Franks, Dirk Wenig, Jan Smeddinck, and Rainer Malaka (2013b). "Sportal: A First-Person Videogame turned Exergame". In: *Mensch & Computer Workshopband: Interaktive Vielfalt.* inter|aktion - Demosession, Mensch & Computer 2013. Oldenbourg Verlag, pp. 543–546
- Benjamin Walther-Franks, Dirk Wenig, Jan Smeddinck, and Rainer Malaka (2013a). "Exercise My Game: Turning Off-The-Shelf Games into Exergames". In: *Proceedings of the 12th International Conference on Entertainment Computing.* Vol. 8215. Lecture Notes in Computer Science / ICEC 2013. Springer, pp. 126–131. DOI: 10.1007/978-3-642-41106-9_15
- Frederic Pollmann, Dirk Wenig, and Rainer Malaka (2014). "HoverZoom: Making On-screen Keyboards More Accessible". In: *Extended Abstracts of the SIGCHI Conference on Human Factors in Computing Systems.* CHI EA '14. ACM, pp. 1261–1266. DOI: 10.1145/2559206.2581173
- Marc Herrlich, Dirk Wenig, Benjamin Walther-Franks, Jan D. Smeddinck, and Rainer Malaka (2014). "Raus aus dem Sessel - Computerspiele für mehr Gesundheit". In: DOI: 10.1007/s00287-014-0825-1
- Nina Runge, Dirk Wenig, and Rainer Malaka (2014). "Keep an Eye on Your Photos: Automatic Image Tagging on Mobile Devices". In: *Proceedings of the 16th International Conference on Human-computer Interaction with Mobile Devices & Services.* MobileHCI '14. ACM, pp. 513–518. DOI: 10.1145/2628363.2634225

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Corrigenda

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- Corrigenda added
- The publication StripeMaps: Improving Map-based Pedestrian Navigation for Smartwatches (Wenig et al., 2015) was replaced with the camera-ready version. All references were updated.

This present version was adapted for online publishing with the following changes:

- In Part II, all the previously included publications were removed from the document.