DYNAMIC PERSONAL SPACES: SUPPORTING GROUP INTERACTIONS AROUND INTERACTIVE TABLETOPS

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ABSTRACT

This master thesis presents a technical solution that allows tracking the presence and location of multiple users around an interactive tabletop. Multiple use cases and scenarios will illustrate how this technology can be employed in order to improve existing interaction designs and also allow for new ones. Based on the concept of territoriality, the author introduces Dynamic Personal Spaces, which are virtual representations of a user's workspace on a table. These spaces can be used to accomplish an automatic display partitioning, coordinate the multiuser process and support group work. Two studies have been conducted based on this approach. A long-term in-the-wild study reveals common distribution patterns of multiple users around a tabletop. An artificial experiment compares dynamic personal spaces with fixed ones in order to study what conditions underly user movements.

ZUSAMMENFASSUNG

In der vorliegenden Master-Thesis wird eine technische Lösung präsentiert, die es erlaubt, die Position von mehreren Personen um einen Multitouch-Tisch herum zu erkennen. In verschiedenen Szenarien wird gezeigt, wie dieser Ansatz es ermöglicht bestehende Interaktionsdesigns zu verbessern und neue zu entwickeln. Basierend auf der Idee der Territorialität werden die "Dynamic Personal Spaces" vorgestellt. Dies sind virtuelle Repräsentationen der Arbeitsbereiche der Benutzer auf einem Multitouch-Tisch. Mit diesem Ansatz lässt sich die automatische Partitionierung der Arbeitsfläche, die Koordination von mehreren Benutzern, sowie die Unterstützung von Gruppenarbeit erreichen. Desweiteren werden zwei Studien vorgestellt. Eine Langzeitstudie im öffentlichen Raum zeigt, welche Verteilungsmuster bestehen, wenn sich mehrere Benutzer an einem Tisch befinden. Ein zusätzliches Experiment vergleicht die Dynamic Personal Spaces mit einer statischen Version um herauszufinden, unter welchen Umständen sich Benutzer um den Tisch bewegen.

CONTENTS

Part I

INTRODUCTION AND FOUNDATIONS

Well Begun Is Half Done

- *Aristotle*

1 INTRODUCTION

Interactive tabletops are a relatively new and promising means to support groups that collaborate towards a common goal. Prior research has shown how groups work together, which factors influence group processes and their outcomes, and how groups can be supported by technology for different types of tasks. An important concept for co-located interactions at and around a table it that of proxemics, also called territoriality. Group members establish and adapt different types of spaces, each with its own distinct area and special purpose. When gathering around traditional tables, these spaces are established by arranging documents and other physical items on the table. However, this strategy is not applicable when working on interactive tabletops with virtual documents and tools. Therefore, current research has studied how this concept can be adapted and transferred to these new conditions.

This is also the goal of the master thesis at hand. After illuminating the wide field of prior research, a new technology will be introduced that is capable of sensing the presence and location of users around a tabletop. Based on this tracking system, the idea of dynamic personal spaces will be introduced. A dynamic personal space is a user interface element that reacts to the presence of a user and provides various advantages, both for single users and groups. Afterwards, the system will be evaluated in two different settings. Firstly, a long-term living laboratory scenario in a museum will reveal arrangement patterns that occur when multiple users are approaching a tabletop. Secondly, an artificial experiment will compare dynamic personal spaces with static ones. The study deals with the question of how dynamic personal spaces influence the movements of users and which processes underly these movements. Finally, a number of use cases will further illustrate how this technology can be employed in order to enhance interactions around a tabletop.

This thesis is an attempt to improve group interactions around a tabletop - either for co-located users interacting in a parallel way, or for groups that collaborate on tightly coupled tasks. The technology presented provides a means for researchers and developers to implement new interaction styles and thereby enhance the user experience during tabletop interaction.

2 THEORIES AND MODELS FOR MULTIUSER TABLETOP INTERACTION

The concepts and ideas in this thesis are based on three research domains: interactive tabletops, group work and territoriality. This chapter will shed light upon the history of these different domains and present some of the relevant concepts and theories. Firstly, research on interactive tabletops will be presented including its history as well as current research topics. The following section will then review important theories for co-located group work, focusing on those models and theories that are most important for the work at hand. Finally, the concept of territoriality will be introduced, including its origins in biological sciences as well as its adoption by social sciences and Human-Computer Interaction (HCI).

2.1 INTERACTIVE TABLETOPS: FOUNDATIONS

Interactive tabletops, sometimes also referred to as interactive surfaces or multi-touch tables, are technologies that combine the power and versatility of a PC with the natural and direct interaction style of touch-sensitive devices. Beyond this technological synthesis, the form factor of a table creates new affordances and possibilities, thereby providing a potential for novel interaction paradigms and work practices for single users and especially for groups. This chapter will provide a short overview over the history, research fields and use cases of interactive tabletops.

2.1.1 *Interactive Tabletops: History*

In 1993, Pierre Wellner introduced *DigitalDesk*, a real desk that is computationally enhanced in order to combine the advantages of digital and physical documents (Wellner, 1993). The DigitalDesk is augmented with a projector that projects digital images onto the desk, and with a camera that can read paper documents and recognize interactions with pens and fingers. Weller presents two example applications, a calculator that allows to enter numbers by pointing at them on real documents, and a painting application which supports copy and paste actions for real paper drawings. Another important early work is that of Fitzmaurice et al., who present ActiveDesk, a rear-projected desktop surface running a graphics application that can be controlled via graspable objects, so-called *bricks* (Fitzmaurice et al., 1995). Bricks serve as physical handles for manipulating digital objects, thereby allowing users to move, transform, scale or bend an object in a more natural way. This approach can be considered as one of the first representatives of what has been later called *Tangible User Interface* (TUI) (Shaer and Hornecker, 2010).

Both of these early research efforts refer to the word "desk" rather than "table" when describing their prototypes. However, this reference was probably not a coincidence: usually, desks are considered working places for a single person, and so are these interactive tabletops. In 1999, Streitz et al. presented the *InteracTable*, an interactive table intended for groups of two to six people (Streitz et al., 1999). It is part of the *i-LAND* environment, which envisioned the workspace of the future featuring interactive walls, chairs and tables. As with previous interactive tabletops, users can interact with the surface using a pen or their hands. However, since this system is designed for multiple users and since there is no designated top or bottom of a table, object orientation becomes a problem. To overcome this problem, objects on the InteracTable can be rotated freely using touch gestures.

Even though these systems were designed for multiple users, a major problem was that of concurrent input. At this time only one or two touch points were supported, which drastically impeded the possibilities of such a system. But even though technologies for detecting multiple touch points date back as far as 1982 (Saffer, 2008, p. 8), the first notable implementation of a multi-touch table occurred in 2001 when Dietz and Leigh introduced their DiamondTouch system. By embedding an array of antennas into the tabletop that transmit a capacitive signal through the user's body to a receiver, it is not only possible to sense multiple touch points, but also to assign these contacts to a specific user (Dietz and Leigh, 2001). A similar implementation that is not able to assign contact points to single users has been presented by Rekimoto (2002). Their system called *SmartSkin* relies on capacitive sensing and can additionally estimate the distance between a hand and the table's surface. In this way, SmartSkin can be used to emulate mouse-like behaviors (e.g. the common "mouse over") that are not supported by standard touch interfaces.

A major problem of these multi-touch systems is that the required hardware is either expensive or hard to manufacture, yet the resulting resolution is still limited. This problem was addressed by Han (2005), who proposed an inexpensive but accurate solution for sensing multiple touches. His approach is based on *frustrated total internal reflection*: infrared light (IR) that is sent into an acrylic pane will be totally reflected, such that it always stays within this pane. As soon as an object touches the pane however, the total reflection is frustrated and the IR light can escape the pane. By installing IR cameras below the pane and applying standard machine vision algorithms, touches and strokes on the surface can be identified. After this technique had been published, a rapid increase of attention to multi-touch interaction occurred. This in turn led to new hardware solutions and interaction techniques contributed by researchers, professionals and hobbyists (Schöning et al., 2010).

With the growing maturity and dissemination of multi-touch sensing technology, commercial products evolved. In 2005, the reacTable was introduced by Jordà et al.. Even though this interactive music instrument mainly works with tangible objects instead of touch, it is worth mentioning because it is one of the few single-purpose products. This means that it is not sold as a multi-touch table that can be used in a variety of settings, but as an actual music instrument. Three years later, Microsoft presented Surface[1], a complete computing platform including an integrated horizontal multi-touch display and a public SDK for application development. In 2012, Microsoft will release the second generation of Surface devices in collaboration with Samsung. Whereas the first generation used rear-projection and IR illumination for touch detection, the second generation employs a new technology called PixelSense[2]. This technology allows every single pixel of a display not only to emit light, but also to sense light. In this way, no rear projection is required which allows a very slim design that fits the entire PC, display and sensing technique into the form factor of an LCD screen. The DiamondTouch table mentioned earlier has turned into a commercial product since 2009 and is distributed by Circle Twelve[3]. Similarly, the InteracTable has reached its third generation and is sold as a finished product by German office furniture manufacturer Wilkhahn[4].

As research continues and commercial products are developed, improved components and procedures, as well as entirely new technologies for interactive tabletops emerge continually. The following section will present some of the most important fields of research that employ and explore multi-touch tables.

2.1.2 *Interactive Tabletops: Fields of Research*

Interactive Tabletops have their origin in different fields of research, most importantly in Human-Computer Interaction and Computer-Supported Cooperative Work (Müller-Tomfelde and Fjeld, 2010, p. 1). Today they play a role in even more research domains, including Ubiquitous Computing and Tangible User Interfaces. This section

1 http://www.surface.com – Microsoft Surface product website. Last accessed 2012-02-26.
2 http://www.microsoft.com/surface/en/us/pixelsense.aspx – Microsoft PixelSense website. Last accessed 2012-02-24.
3 http://www.circletwelve.com/products/diamondtouch.html – Circle Twelve DiamondTouch product website. Last accessed 2012-02-24.
4 http://www.wilkhahn.com/loadframes.html?/2_produkte/2142.htm – Wilkhahn InteracTable product website. Last accessed 2012-02-24.

will outline some of the work in these fields with a focus on current research topics and trends.

Human-Computer Interaction (HCI) is a wide research topic that incorporates various scientific disciplines like psychology, industrial design, ergonomics and engineering. Within this wide area of research, many uses of interactive tabletops exist within it. Since HCI is one of the original disciplines dealing with interactive tabletops (Müller-Tomfelde and Fjeld, 2010), research on this topic is very mature. Tabletops are not exclusively an object of investigation but are already employed as a "common" approved technology that provides a base for further research. The following publications illustrate the wide array of applications for tabletops in HCI. Hartmann et al. (2009) have conducted a long-term in-the-wild study of a multi-user tabletop tourist application. Schwarz et al. (2011) are employing multi-touch tables in control rooms where they could improve workflows by enhancing the navigation of road networks. In yet another work, Geyer et al. (2011) are presenting a digital workspace for collaborative design activities that employs a high-resolution wall display and a multi-touch table and that offers special interaction techniques for supporting these activities.

Computer-Supported Cooperative Work (CSCW) is another scientific discipline that includes research topics from many fields like computer science, social sciences, psychology and media studies, amongst others. It evolved in the late 1980s and has been defined as "an endeavor to understand the nature and characteristics of cooperative work with the objective of designing adequate computer-based technologies" (Bannon and Schmidt, 1989). Thus, the subject of CSCW research is how computers and other digital devices can be used to improve and enhance collaboration. An important distinction in CSCW is that between remote and co-located collaboration. Interactive tabletops are mostly considered for the latter case due to their inherent properties and affordances. Tables are objects around which people traditionally gather when discussing problems, planning activities or working on a task together. The inclusion of interactive tabletops into CSCW research is therefore understandable.

In 1991, Mark Weiser published his seminal paper on the computer of the 21st Century in which he introduced the paradigm of *Ubiquitous Computing* (UbiComp), an approach that "takes into account the human world and allows the computers themselves to vanish into the background" (Weiser, 1991, p. 94). It is based on the idea that there will be hundreds of computers in different forms like workstations, pads, tabs (what today we would call a smartphone) and horizontal displays, all of them integrated into the surrounding architecture and into everyday live and connected by a giant wireless network. Even though there were no horizontal displays in this original scheme, they soon became an integral part of Ubicomp. Today, interactive tabletops are an integral part of many UbiComp research projects (e.g. Streitz et al. (1999), Shen et al. (2003), Wei et al. (2011)). Besides implementing applications for concrete scenarios, researchers also work on high-level frameworks that allow other researchers to create their own UbiComp application. Collins et al. (2011) for example are developing the Cruiser Framework for creating tabletop applications. One important characteristic of this framework is that it supports a multitude of hard- and software platforms (e.g. Windows, OSX and Linux as operating systems; DiamondTouch, PQ Labs[5] and Kinect for Xbox 360[6] as hardware platforms), thereby allowing for the development of very flexible UbiComp applications that work with many different devices.

Another domain that heavily relies on interactive tabletops is that of Tangible User Interfaces (TUIs). The basic assumptions behind TUIs is that human beings possess highly specialized skills that allow them to sense and manipulate their immediate physical environment. However, common user interfaces of digital devices do not make use of these innate skills. Even worse, interactions with standard graphical user interfaces (GUI) are inconsistent with interactions in our natural environment (Ishii, 2008). In order to overcome this limitation, TUIs rely on tangible objects that allow users to control digital devices by employing these advanced skills. By giving a physical form to digital information, it can be perceived and manipulated more easily and more naturally (Ishii, 2008). When TUIs are combined with tabletops, researchers often use *tokens*, which are "discrete, spatially reconfigurable physical objects that represent digital information or operations" (Ishii, 2008, p. xix). For example in the Facet-Streams application by Jetter et al. (2011), users employ tokens in order to create and manipulate boolean queries in a collaborative setting. The reacTable system (Jordà et al., 2005) also relies heavily on tokens for controlling and manipulating a virtual synthesizer. Another advantage of TUIs is that they can help resolve ownership conflicts and promote turn taking behavior concerning digital artifacts (Olson et al., 2011).

2.2 GROUPS INTERACTING WITH TABLETOPS

After illuminating the history and state of the art of interactive tabletops, this section focuses on how such systems can support group work. In the beginning, some underlying concepts will be illustrated including the basic categories of group work as well as the types of tasks that can occur when people work together. Afterwards, some important processes that occur during group work will be described including task coupling, awareness and social protocols.

5 http://multi-touch-screen.com/ – PQ Labs Multi-Touch Technology website. Last accessed 2012-02-28.

6 http://www.xbox.com/en-US/Kinect – Kinect for Xbox 360 website. Last accessed 2012-02-28.

2.2.1 *Cooperation, Coordination and Collaboration*

In general, the word collaboration is used to describe a situation where people work together in order to reach an objective. Similarly, cooperation and collaboration are often used interchangeably in everyday language. In a scientific context however, there are important differences between these two terms.

Roschelle and Teasley (1995) for example provide the following distinction between collaboration and cooperation: when work is divided amongst group members, such that each member is responsible for their own discrete work package, it is considered cooperation. In this case, coordination between group members is only required for the compilation of these discrete work packages. Collaboration, on the other hand, requires constant coordination between group members and is based upon a mutual commitment to the task at hand. Collaboration thus is defined by the authors as "a coordinated, synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem" (Roschelle and Teasley, 1995, p. 70).

One problem that arises with this definition is that during collaboration, there will nevertheless be a certain extent of individual, uncoordinated work. For example, the process of sense-making is often an internal, individual process. Members of a group that is confronted with a new problem might start their work by thinking about this problem and trying to understand it – by themselves. Should this process be considered as collaboration or cooperation? The underlying question is whether collaboration and cooperation are mutually exclusive. Brna (1998) approached this issue by introducing what he called the *collaborative state*. He argues that collaboration should be seen both as state and as process. Applying this model to the previously mentioned example, the group members – whilst thinking about the new problem for themselves – are in a cooperative process, that is nevertheless part of a higher-level collaborative state that is maintained all along.

Besides cooperation and collaboration, there is also coordination. In Roschelle's definition, coordination is a means to an end, an action that is required in order to successfully cooperate or collaborate. However, there are alternative views on coordination. For example, Winer and Ray (1994) sees coordination as the central part of a three-part continuum. This continuum ranges from low to high intensity, where intensity refers to multiple dimensions: risk, required time, and opportunity. At the lower end of the continuum, there is cooperation. According to the author, cooperation is directed towards short-termed goals and is based on an informal relation between members. There is no evident high-level goal or structure, and members of a cooperatively working group share only task-related information. Since each member manages his own resources, cooperations bear very little risk. Coordination is the second, central part of the continuum. It comprises more formal relationships as well as a common goal. There is more structure both in terms of organization and responsibilities. An increased amount of communication is required, and since resources are shared amongst member, risk increases. Finally, collaboration is considered to be at the high intensity end of the continuum. Here, high-level goals are pursued over a longer time period, leading to increased commitment and a greater need for communication, organization and sharing of resources.

After pointing out the existing distinctions between cooperation, coordination and collaboration, the next chapter deals with the different types of tasks that can occur when people work together.

2.2.2 *Classification of Group Tasks*

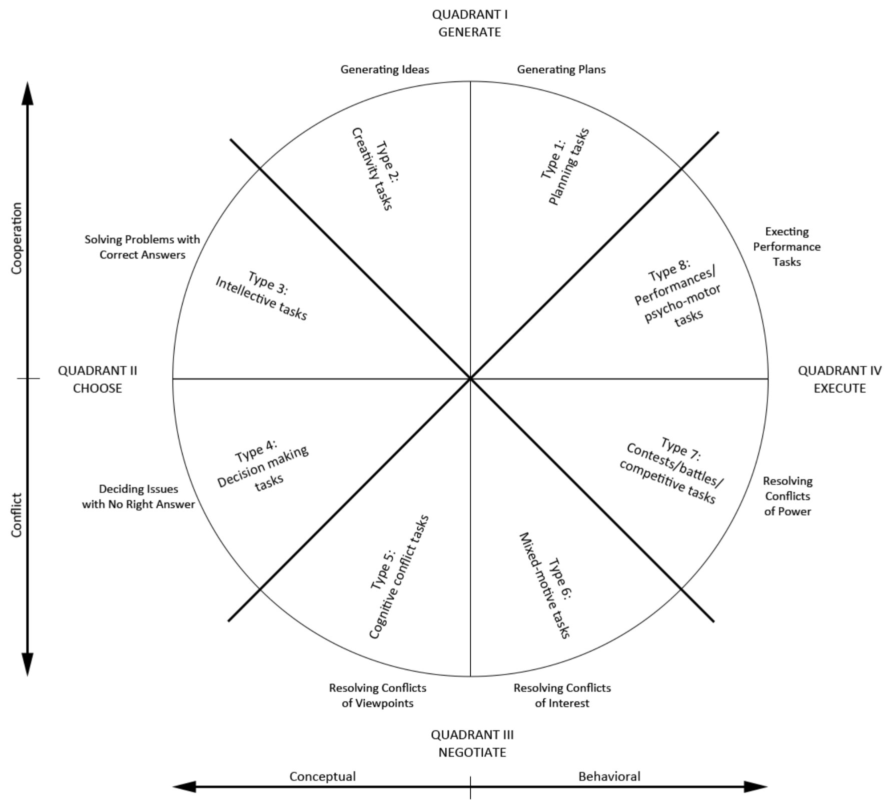
When studying group interactions, one needs to take into account that the type of a task will have an influence on a group's performance and outcome. This is because each task type requires different strategies and capabilities from the group members. Therefore, it is important to classify the tasks into task types and to investigate how each influence group performance. In order to classify a task, there are many different dimensions that can be considered. For example, a task can require either physical performance or cognitive efforts, or group members can work on a task in either a collaborative or a competitive way.

There has been a lot of research dealing with models and categories for task classification, beginning as early as the 1950s. However, the history of these research efforts will not be elaborated at this place (the interested reader shall be referred to McGrath (1984, pp. 54–60)). Instead, this section will focus on the *Group Task Circumplex*, a model for task classification that was proposed by McGrath (1984). This sophisticated model builds up on and extents prior research and is widely distributed and often referred to within different scientific disciplines. It was not only created in order to classify, summarize and compare existing research on group task performance, but also to support researchers during the design and analysis of new studies.

Figure 1 shows an overview of the Group Task Circumplex. There are eight different task types, which can be classified based on the following dimensions:

- Quadrant: there are four quadrants that represent high-level task types: generate, choose, negotiate and execute.
- Horizontal sector: tasks towards the left semi-circle are rather conceptual or intellectual, whereas those in the right semi-circle tend to be more behavioral or action-based.

Figure 1: The Group Task Circumplex by McGrath (1984, p. 61)



- Vertical sector: tasks towards the upper semi-circle have a collaborative character, whereas tasks in the lower semi-circle rather imply conflicting behavior.

This model can be used for both planning an evaluation and analyzing its results, depending on the use case. By classifying a group's task, a researcher can predict what types of behaviors and interactions will occur most likely. Conversely, if a researcher wants to observe a certain type of behavior, she can select an according task and in this way increase the probability that the intended behavior occurs. This model can also be employed when implementing a collaborative system, for example in order to check if all relevant task types are supported appropriately.

Independent of the high-level task type, group work is based on a number of basic processes that are crucial for successful collaboration. The next chapter will therefore provide details on some of these processes and the role they play for tabletop interactions.

2.2.3 *Task Coupling and Awareness*

Task coupling and awareness are two related concepts in the field of collaboration (Tang et al., 2006) and play an important role for the design and evaluation of collaborative systems. In so-called *mixed-focus* situations (Gutwin and Greenberg, 1998), group members repeatedly switch between individual and group work. In order to collaborate successfully, they have to coordinate their activities and share relevant information (Dourish and Bellotti, 1992). This coordination process is based on *awareness*, which is "an *understanding of the activities of others*, which provides a *context for your own activity*" Dourish and Bellotti (1992, p. 107). Awareness is however not an act of explicit communication. Rather than that, contextual information is passively perceived and evaluated. This contextual information can for example be based on artifacts in the workspace or on actions and gestures performed by other people. Dourish and Bellotti (1992) distinguishes between high-level awareness and low-level awareness. The first deals with the *character* of activities – which task is handled by whom – and allows to structure the group's activities. The latter is about the *content* of a task, which is for example required when multiple people write a single piece of text.

Switching between individual and group work during mixed-focus tasks usually occurs when subtasks require a different level of *coupling*. Task coupling is a process that is related to workspace awareness and "refers to the dependency of participants on one another—when participants cannot do much work before having to interact, the work is tightly coupled; conversely, when participants can work independently for long periods of time, the work is loosely coupled" (Tang et al., 2006, p. 1182). Dourish and Bellotti (1992) observed that transitions between tightly and loosely coupled work occur frequently and seem to be based on the awareness of others' activities. Yet it is not possible to foresee when these transitions will arise exactly.

Tang et al. (2006) found that coupling style influences a number of factors during co-located tabletop interaction. Firstly, the arrangement of users changes along with coupling style, where tight coupling leads to closer arrangements and loose coupling leads to greater distances between users. It was also observed that users establish territories (see chapter 2.3 hereafter), but that these territories are impermanent as they moved along with the users. Furthermore, it was observed that interferences between users were less frequent during tightly coupled work and that they were resolved in a more fluid and considerate way compared to interferences that occurred during loosely coupled tasks. Finally, Tang et al. observed that the type of task as well as the tools available can influence coupling styles.

When groups work together at a tabletop, some kind of coordination is required such that group members do not interfere with the work of each other. This coordination process is largely based upon social protocols and coordination mechanisms, which are the subject of the next section.

2.2.4 *Social Protocols and Coordination Mechanisms*

In 1999, Stewart et al.. introduced the term *Single Display Groupware* (SDG) as a new model for co-located collaboration (Stewart et al., 1999). The authors define SDG as a computer-based approach to support co-located collaboration that relies on a single display and multiple input devices. It is thus a model that describes the predecessors of interactive tabletops, which also rely on a single display and support multiple, parallel inputs via touch. Such systems come with a number of advantages compared to standard PCs like the ability to work in parallel without a need for turn taking and an increased level of awareness. However, Stewart et al. also identify potential problems that can occur with SDG. Most importantly, the authors state that new types of conflicts may arise because parallel interactions allow users to execute incompatible operations.

In order to overcome these new conflicts, one can think of two principal approaches. Firstly, the resolution of conflicts can be handed over to the group. In this case, group members need to establish and follow a set of *social protocols* that either avoid conflicts or help resolving them. Secondly, conflict resolution can be handed over to the system, which must then implement a number of *coordination mechanisms*.

Izadi et al. have developed Dynamo, an interactive system for information sharing that primarily relies on social protocols for conflict resolution (Izadi et al., 2003). When evaluating their system, they observed so-called *overlap* situations where user interactions interfered with each other. These situations occurred especially during phases of high concurrent activity. Even though the system provides basic coordination mechanisms, most of the coordination was achieved by establishing social protocols. These social protocols were usually developed very quickly by asking other group members for consent before triggering an action, or by making others aware of an overlap situation.

Even though Izadi and his colleagues observed that social protocols work as a means of conflict resolution, other researchers argue that this approach is not sufficient in many situations. Morris et al. (2004) have observed groups interacting with different tabletop applications and identified a number of recurring conflicts. These conflicts can occur in relatively simple situations and despite existing social protocols. Therefore, the authors argue that additional coordination mechanisms provided by the system are required. In order to better structure the problem at hand, they propose different dimensions for classifying both conflict type and resolution strategy (Morris et al., 2004, p. 263). The type of a conflict can either be *global* (actions affecting the entire application), *whole-element* (actions affecting access to single objects) or *sub-element* (actions affecting object contents). In order to resolve such conflicts, three different strategies can be employed. A *proactive* strategy allows the initiator of an action to define its outcome. When applying a *reactive* strategy instead, all group members except the one who triggered the conflicting action decide on how to resolve this situation. Finally, *mixed-initiative* strategies involve the entire group in order to resolve a conflict.

This chapter presented a number of important ideas and theories for group work that also need to be considered when designing applications for co-located collaboration around interactive tabletops. One very striking property of work on a tabletop is that people tend to establish territories within which they gather their resources and interact with them. This concept of territoriality has a long history, which will be the topic of the next chapter.

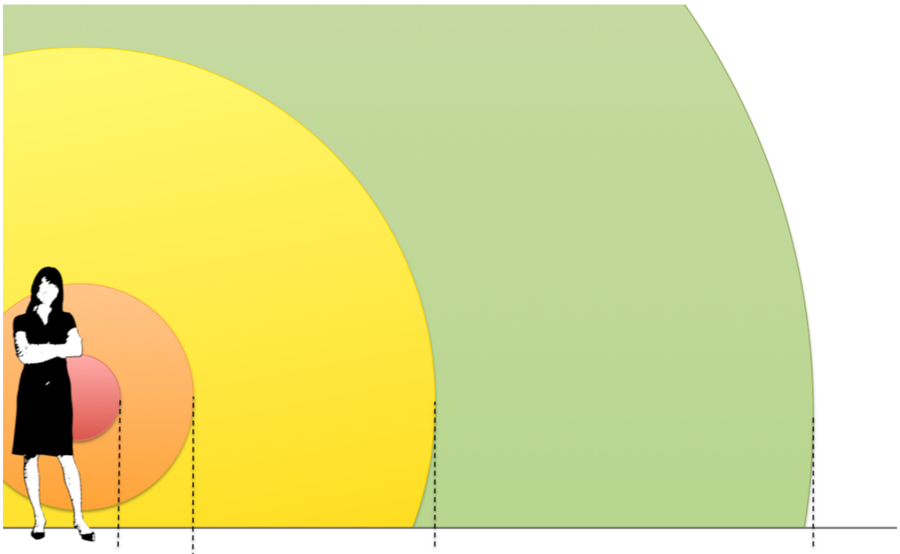
2.3 THE CONCEPTS OF TERRITORIALITY AND PROXEMICS

> "There can be no doubt that the desire for acquisition of a definite territorial area, the determination to hold it by fighting if necessary, and the recognition of individual as well as tribal territorial rights by others, are dominant characteristics in all animals. In fact, it may be held that the recognition of territorial rights, one of the most significant attributes of civilization, was not evolved by man, but has ever been an inherent factor in the life history of all animals." – (Heape, 1931, p. 74)

2.3.1 *Territoriality in Biology and Social Sciences*

The concept of territoriality originated in ethology, which is a branch of biology that deals with the scientific study of animal behavior. One of the first publications devoted to this topic was *Der Vogel und sein Leben* by German priest and zoologist Altum (1868). However, the concept of territoriality did not spread into the scientific community until Howard's seminal book *Territory in bird life* was published in 1920 (Howard, 1920). Altum and Howard discovered that male birds, returning from their seasonal migration, do not fight against each other over females but over territory. As the concept of territoriality spread amongst biologists, so did research on this topic. Nearly 100 years after Altum's first insights, Hediger enhanced the view on territoriality by shifting from an external to an internal point of view (Hediger, 1955). Whereas an external view on territoriality is focused on a geographical space (e.g. a pasture or a zoo compound), an internal view focuses on territories relative to the animal. This so-called personal space can be distinguished from geographical territories in a number of ways. First of all, personal space is centered around the animal and is therefore moving along with it, whilst territories are usually static.

Figure 2: A visualization of Hall's distance zones (Hall, 1966)



Secondly, the borders of a territory are usually perceivable, for example through odor (animals marking their territory) or visually (a human's house and yard), whereas personal space is imperceptible. A common analogy for personal space is that of a soap-bubble surrounding an individual. Hediger defines four different spaces or distance zones with different implications:

- *Flight distance*: when an animal B crosses the boundary to the flight zone of animal A, which is of a different species, A will try to take flight from B.
- *Critical distance*: given animal A above cannot take flight and B continues approaching, A will eventually reverse its behavior and approach (and ultimately attack) B.
- *Personal distance*: this is the habitual distance which separates single members of the same species in normal situations.
- *Social distance*: in order to avoid losing contact with its fellows, an animal will not diverge from the group beyond this distance.

In 1966, anthropologist Hall transferred Hediger's approach to human beings and therefore into social sciences by introducing a new concept named *proxemics*. Proxemics deals with "*the interrelated observations and theories of man's use of space as a specialized elaboration of culture.*" (Hall, 1966, p. 1). In his book, Hall first summarizes different aspects of animal territoriality like distance regulation mechanisms, crowding and social behaviors. He then moves towards human beings and analyzes in which ways space can be perceived by the human body: eyes, ears and nose serve the perception of space at a distance, whilst skin and muscles allow for perception of immediate stimuli. He even moves one step further by analyzing the subjective human perception of distances by looking at pieces of art and literature. All these observation lead to the book's essence, which is a definition of the human's four different distance zones and their properties (see also Fig. 2) (Hall, 1966, chap. 10):

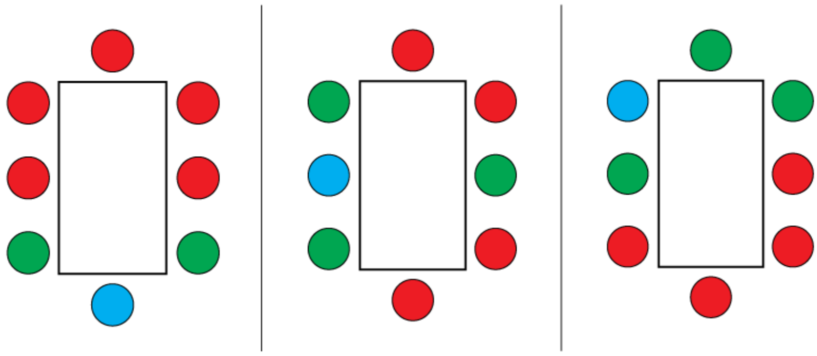
- *Intimate distance* (0-46cm): in uncrowded situations, usually only good friends and life partners are allowed within this distance. The presence of a person within this distance is conveyed by a multitude of sensory perceptions like smell, sound and body heat.
- *Personal distance* (46-120 cm): this zone begins just outside easy touching distance and is for example used for discussion of personal interest.
- *Social distance* (120-370 cm): when people interact with each other at such range that direct contact is not possible, they are within social distance. This is the usual space for casual social gatherings as well as impersonal business.
- *Public distance* (370-760 cm): people within public distance will be perceived consciously, but are usually not involved in any kind of interaction. This is for example a distance kept between a public speaker and the audience.

Hall further divides each distance zone into a close phase and a far phase and defines a number of properties for each of them, for example visual perception (what part of another person's body lies within the visual field and what level of detail can be seen), voice volume and olfactory cognition. The distances provided by Hall are of course no exact numbers - they change with influences like age, gender or social status. Most importantly, the distances provided are based on observations made in the US. Therefore, they cannot be transferred into other cultures easily since culture is one of the main influencing factors for these distance zones (Hall, 1966, p. 188).

2.3.2 *Territoriality around Tabletops*

With the transition from zoology to psychology and social sciences, the occurrence of territoriality and proxemics were discovered and examined in various contexts. One of those contexts is the psychology of small group behavior. A number of researchers have investigated how space allocation and seating arrangement around a table influence different group processes, and vice versa. The following sections will give an overview of this research and its results.

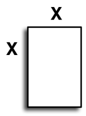
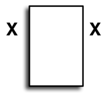
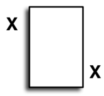
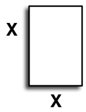
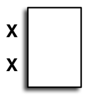
Figure 3: Seating arrangements used by (Sommer, 1959). Blue: subject seating position; green: close chair; red: distant chair



One of the first researchers to discover the role of seating positions in group discussions was Bernard Steinzor Cummings et al. (1974). During his research on the development of a measure of social interaction, he observed a participant shifting to a different seating position due to an argument with another participant. This occurrence gave rise to further research and a new hypothesis, stating that seating arrangement in a small group influences which group members are more likely to interact with each other (Steinzor, 1950, p. 552). His experiment with discussion groups of ten members sitting at a round table confirmed his hypothesis. Steinzor could show that, in general, the degree of interaction is higher than expected by chance for two participants facing each other. Conversely, it is lower than expected by chance for two adjacently located participants. He argues that this is due to the fact that participants sitting more opposite to each other are exposed to a higher level of physical and expressive stimuli, thus evoking a stronger reaction to the actions of each other. In 1957, Hearn showed that the Steinzor effect depends on the type of leadership present in a group (Hearn, 1957). As formal leadership increases, the Steinzor effect decreases. In this case, group members are more likely to interact with adjacent people and less likely to interact with people located opposite to them.

Nine years after Steinzor's initial efforts, psychologist Robert Sommer started studying the interplay of proxemics and group interactions around tables more thoroughly. During his first studies, he conducted observations and experiments on seating arrangements that occur during discussions at a table (Sommer, 1959). Sommer discriminates two seating arrangements: neighboring chairs (also "close chairs") include the two directly adjacent chairs (including "around the corner" arrangements) as well as the opposite chair (unless the opposite chair is across the long side of the table). All other chairs are considered "distant chairs" (see Fig. 3). The main outcome of his observations in a hospital staff dining hall was that the intensity of interaction between two people is higher for close chairs than for distant chairs.

Figure 4: Seating preferences at rectangular tables (Sommer, 1965, p. 342)

Seating Arrangement	Conversing	Cooperation	Co-Acting	Competing
	42	19	3	7
	46	25	3	41
	1	5	43	20
	0	0	3	5
	11	51	7	8
	0	0	13	18

Furthermore, he discovered that there is also a ranking within the close chairs: there is more interaction between corner positions than between adjacent or opposite chairs. In a follow-up experiment, Sommer asked groups of two and three participants to enter a room and sit down at a table in order to discuss various topics. The experiment supported his prior observations since a significant majority chose to sit at corner positions.

In the context of group interactions around a table, another work of Sommer needs to be mentioned here. His paper "Further Studies of Small Group Behavior" reports on an observational study and a questionnaire study which focus on preferred seating arrangements of dyads (Sommer, 1965). The questionnaire asked 151 psychology students for their preferred seating arrangement at a rectangular table with six predefined chair positions. Every participant had to provide one arrangement for each of a number of conditions: *conversing* (talking to each other before class), *cooperating* (studying together for a joint exam), *co-acting* (studying for different exams) and *competing* (a puzzle solving contest). Figure 4 shows the resulting seating preferences and their corresponding percentages.

Using the terms of close chairs and distant chairs mentioned above, one can see that conversing and cooperating dyads strongly prefer close chairs (99% and 95% respectively). On the other hand, co-acting dyads tend to prefer distant chairs (59%), whereas the preference of competing dyads is best formalized as opposite (59%). As Sommer aptly puts it,

> "There is a metaphorical quality to these arrangements with people competing sitting 'in opposition,' people cooperating sitting 'on the same side,' people conversing sitting 'in a corner' and people co-acting choosing a 'distant' arrangement." (Sommer, 1965, p. 343)

The factor which influences the selection of seating arrangements the most is eye contact, according to Sommer. During conversations, eye contact is desirable, as well as being in close proximity to the other person. Therefore, near opposite or around the corner arrangements are mainly chosen. During cooperation, people want to share working materials and discuss issues; however, eye contact is considered rather disturbing most of the time because one might get distracted more easily or feel like being watched. Due to these reasons, a majority choose to sit next to each other. The same reasons apply during co-action. Given the fact that the two persons are working independently however, the majority switches to a far diagonal arrangement that maximizes the working area whilst minimizing the chance of eye contact. Finally, competition again requires eye contact. One rather subconscious reason for this is that eye contact is considered as a sign of strength or hostility in many species. The other, more conscious reason is that eye contact allows each participant to monitor the actions and progress of his opponent. Therefore, opposite arrangements are chosen most of the times for these kind of tasks.

Other researchers have expanded these studies on additional factors that have an impact on spatial arrangements and vice versa. These research efforts reveal that culture, sex and acquaintance do influence how people arrange around tables (Cool, 1970). It was furthermore shown that the spatial arrangement of a group is an important factor in leadership emergence (Howells and Becker, 1962), and that the level of leadership in a small group negatively correlates with the speed of finding a consensus solution and the quality of this solution (Cummings et al., 1974).

This section provided an overview of various research efforts that deal with the bidirectional nexus between spatial arrangements around tables and group processes. It is obvious from the results that there is a strong connection between those two elements. Therefore, the insights gained for traditional tables should also be considered when designing interactive tabletops, especially when targeting small groups working together. To conclude this section, the reader is once more referred to Sommer, who states that

> "spatial arrangement is a function of group task, the degree of relationship of individuals, personalities of the individuals, and the amount and kind of available space. The resulting arrangement in turn affects communication, friendship, and status differentiation between individuals." (Sommer, 1967, p. 145)

Terminology: Territory versus Space

Before looking at what happens *on* a table surface, it is necessary to clarify the terms used in these contexts. So far, there has been a clear distinction between territoriality and proxemics. Territoriality deals with animal and human behavior that aims at establishing and maintaining a fixed area where they live - a territory. Proxemics on the other hand deals with zones or spaces that are relative to an animal or a human being. They move along with their "owner" and influence different social behaviors.

However, this distinction is not used consistently in research. For example in some HCI-related publications that will be cited in the following sections, the terms *territory* and *space* are used interchangeably despite their different origins. However, this thesis builds upon the theory of proxemics only and does not further deal with territorial behavior as defined by biologists. Therefore, in order to avoid any confusion, the terms territory and space (as in personal space) will be used interchangeably hereafter.

2.3.3 *Territoriality upon Tabletops*

The previous section has shown how the concepts of territoriality and proxemics apply to spatial arrangements around tables. These insights are important to consider when designing interactive tabletops for multiuser scenarios. However, one does not only need to consider what happens around a table. It is equally important to look at the things that happen on its surface. A number of researchers have dealt with this topic, and in the following paragraphs the ideas and concepts discovered in their research will be discussed.

A seminal publication that deals with what happens on a table during group interaction is Tang (1991). He analyzed the activity of small groups during a shared drawing activity in order to derive guidelines for the design of tools that support collaboration. Tang observed that group members would use spatial orientation of objects in order to convey additional information. When addressing other group members, one would draw either close to an existing drawing of that person or orient the new drawing towards that person. In this way, an evident context can be established without the need for explicit communication. Similarly, people would deliberately draw small and close to themselves in order to express that their drawing is considered a personal idea that is not intended for discussion. In this way, group members can establish different spaces that carry different meaning depending on their location and the orientation of items.

Orienting artifacts relative to each other does of course require a shared workspace. Such a shared workspace does however come with its own issues, the most important being that objects within the shared space appear upside down for at least some of the members. This aggravates readability, understandability and in the end collaboration. Thus, Tang recommends common views of the shared space that present objects aligned to the user. Finally, Tang emphasizes that concurrent access to the drawing space is a crucial factor for collaboration. When group members can access the workspace concurrently, their actions serve as a resource that helps organizing group activities. Concurrent access also allows for parallel work, which leads to increased efficiency as well as reduced competition amongst group members.

The role of artifact orientation during group work was further examined by Kruger et al. (2003). Based on their study on collaboration and inspired by prior research including that of Tang (Tang, 1991), the authors identify three roles of orientation. *Comprehension* is connected to orientation because orientation influences the readability of items as well as the ease of accomplishing tasks. For example, it is easier to annotate an object when a user can rotate it towards her so she does not need to write upside down. The orientation of an object can also be a means of *communication*. A person who orients an object towards herself expresses different intentions than a person who orients an object towards the group. Kruger et al. state that object orientation can be regarded as a stand-alone act of communication since a majority of test subjects applied and understood a change in orientation without the need for additional (e.g. verbal) communication. *Coordination* finally is a role of orientation that directly connects to the theories of territoriality and proxemics. According to Kruger et al., coordination of objects is used to establish different types of spaces. *Personal spaces* are established by orienting objects towards oneself while keeping the distance to these objects on the table at a minimum. This makes it easier for the "owner" of these objects to access and work with them, while it is harder for other group members. The so-delimited space is however not only a visual feature. In fact, Kruger et al. observed that other group members would not perform any actions within another's personal space. *Group spaces* on the other hand can be accessed by multiple (or all) members of a group. Such spaces are located more central in order to increase their accessibility. The orientation of objects within the group space is usually the result of a negotiation between the participants and can significantly influence task completion ((Kruger et al., 2003, p. 373). The establishment of different spaces supports group members in noticing who is working with which resource and which resources are available for all group members. Thus, personal and group spaces also play a role in group awareness (see chapter 2.2.3).

The research of Kruger et al. has been extended by Scott (Scott, 2003), who added a third type of space that is used for storing artifacts. Based on Scott's observations, these so-called *storage territories* are located near the table edges. In this way, items stored within these territories can be easily accessed by adjacent group members while they do not disrupt the order of items in the other spaces. In 2004, Scott et al. (Scott et al., 2004) expanded this work by conducting a detailed analysis of both spatial and functional properties of the different territory types.

According to the authors, personal territories are used to reserve both table space and artifacts on the table surface. With respect to group work, personal territories support individual, independent activities that relate to the group task and therefore serve as a group resource, since other group members can observe personal spaces in order to keep track of other user's activities. The authors confirm Kruger et al.'s 2003 observation that people tend to establish their personal territories at the table edge zones directly in front of them. Scott et al. state five factors that can influence the size and shape of a personal territory: number of collaborators, size of the table, task activities, task materials and visible barriers (Scott, 2003, p. 391). Besides those quantitative factors, social norms and protocols do also play a role for the creation and maintenance of personal spaces.

Group territories are used to perform activities that concern two or more group members. For example group members would work within this territory when they want to help another group member or when the entire group is working on the main task activity. Group territories are also used to transfer or deposit task resources. How group territories are utilized does also depend on the extent of coupling (see chapter 2.2.3). During loosely coupled tasks, the group territory is further partitioned to allow parallel work on the final outcome. When a task is tightly coupled, the entire group space is utilized and the placement and orientation of artifacts is used heavily in order to provide additional context and information. Every area on a table that is not a personal territory is considered as group territory. Therefore, the size of the group territory depends on the same factors as personal territories.

The purpose of storage territories finally is to store both task-related (artifacts and tools) and non-task items (e.g. drinks). Whereas group territories and personal territories are mutually exclusive, storage territories seem to exist "above" these territories, such that they can exist on top them. Storage territories are highly mobile and can also be created and removed dynamically during group work. A storage territory inherits its accessibility from the underlying territory. If it is located within a personal territory, the stored items belong to the owner of that territory. If it is located within the group territory, all group members are allowed to access the contained objects.

3 MOTIVATING DYNAMIC PERSONAL SPACES

The previous chapter has shown how tabletop users partition the workspace into different zones and that these zones play an important role for coordinating multi-user activities and for mediating awareness information. Furthermore, we have seen that people working at the same table prefer different seating arrangements depending on the task at hand. Combining these two insights has led to the idea of *Dynamic Personal Spaces* (DPS). A DPS is a virtual representation of a users personal space that can take many shapes. The underlying idea is that a DPS shall appear automatically right in front of the user as she approaches an interactive tabletop. When the user moves around the table, the DPS shall follow all of her movements. And finally, when the user leaves, the DPS shall disappear automatically.The goal of this approach is to provide a personal space to every user of a tabletop in an easy and accessible way.

DPSs can be implemented in a variety of ways. One could think of a very simple DPS that visually indicates a personal work area and thereby partitions the entire screen estate. More elaborate approaches could function as a container for digital objects and provide personal toolbars and controls to each user in order to minimize conflicts. Another step further, DPSs could provide functions that are dependent on the location of a user, or they could be combined with other technologies like user identification.

Transferring the DPS concept to a multi-user scenario means that group members can stand far away from each other during loosely coupled tasks, such that each of them can work independently without interferences by others; and they can move close together for tightly coupled tasks in order to allow for more efficient communication and information sharing. In both cases, each DPS will follow his owners movements, carrying along the tools and artifacts contained in it and automatically partitioning the table's surface into distinct areas.

The DPS approach covers multiple guidelines for co-located, collaborative work on tabletops as proposed by Scott et al. (2003, p. 163). According to the author, tabletop technologies must support multiple types of transitions, namely transitions between different activities and transitions between individual and group work. DPSs can support these transitions especially if they also come with a rearrangement of users. Since DPSs can serve as a container for digital artifacts, all digital work materials will stay with its owner all the time. Thus, less interactions are required if a user wants to move to another spot, which in turn increases efficiency. Assuming that all work materials are contained in a user's DPS, no interactions are required at all – the act of moving to another location is sufficient by itself. A second guideline proposed by Scott is that a tabletop system should support flexible user arrangements. This guideline is also implemented by the DPS approach, since the support for movements of users and rearrangements of groups is the central point of this approach. Finally, tabletop systems should also support simultaneous user interactions. Such parallel interactions can be facilitated by the DPS approach because the work area is automatically partitioned into different spaces. These spaces can in turn help to organize and coordinate parallel activities on the table.

Similar to Scott et al.'s guidelines, Tang et al. (2006) states four different implications for tabletop design. One of them is that tabletops should provide "mobile high resolution personal territories" (Tang et al., 2006, p. 1190) in order to minimize overlap situations. The authors suggest to do so by employing a higher resolution workspace or by using additional external personal displays. Even though the idea of creating personal territories automatically based on the presence of a user is not mentioned, it is clear that the DPS approach completely covers the demands posed by the authors .

Another issue that can be addressed via the DPS approach is that of document orientation. Assuming a DPS that works as a container, newly added documents can automatically be aligned towards the user. In this way, efficiency can be increased because less steps are required in order to position an object correctly. However, it has to be considered that in some scenarios this automatic orientation should only occur initially. Users should be able to reorient their documents as they wish because document orientation can also serve as an important means for comprehension, coordination and communication in collaborative settings (Kruger et al., 2003).

The first step towards DPSs is to implement a tracking system that is able to detect the presence and location of users around an interactive tabletop. The implementation of such a tracking system is covered in the first chapter of the following part. Afterwards, the application of the tracking system and DPSs in a public exhibition will be presented to the reader. The final chapters of the next part will then cover two different types of evaluation: an evaluation of logging data collected throughout the exhibition as well as a lab experiment that focuses on the basic properties of DPSs and how they are employed during group work.

Part II

IMPLEMENTATION AND EVALUATION

Nothing is more revealing than movement

- Martha Graham

4 BUILDING A TABLETOP-INTEGRATED TRACKING SYSTEM

In order to realize DPSs, an interactive tabletop needs to be able to sense the presence and location of a user. This chapter will describe the design and implementation of such a tracking system. Firstly, the requirements for such a system as well as the existing hardware solutions will be identified and evaluated. Afterwards, the hard- and software implementation of the tracking system will be described in more detail.

4.1 REQUIREMENTS ANALYSIS AND DESIGN ALTERNATIVES

Before implementing a tracking system for multitouch tables, one has to think about the requirements that exist for such a system. During the early hardware design phase, a number of requirements have been collected. These are summarized in the following list[1] :

- **Common Interface**: Different people who want to utilize the tracking system might want to use different technologies to connect to it. Therefore, the tracking system should have a common interface that is recognized by most hardware components and supported by a majority of programming languages.
- **Accuracy**: Accuracy might not always be necessary, especially for simple use cases like detecting the arrival or departure of a user independent of her exact location. However, high accuracy results can always be transformed into low accuracy results, but not vice versa. Therefore, a tracking system with high accuracy should be preferred.
- **Mobility**: Even though multitouch tables are in the ascendant, they can not yet be considered a common technology found in a majority of public spaces. Therefore, tabletops are often moved from one location to another, as it is especially the case for trade shows, exhibitions and conferences. The demand for mobility leads to constant product improvements which yield less weight and easier setup, amongst others (e.g. Microsoft Surface 1 vs. Microsoft Surface 2). This demand should also be considered when designing a tracking system for tabletops. In this case, mobility means that the tracking system should be easy to move and set up, ideally being a permanent component of the table in order to reduce complexity.

1 The order of requirements does not represent their importance.

Table 1: Fulfillment of requirements by different techniques.

	Calibration Free	Common Iterface	Accuracy	Mobility	External Factors	Robustness
Rotational Laser						
Pressure Mats						
Range Camera						
Distance Sensors						

- **Calibration-Free**: Some tracking systems, especially those using multiple cameras, require a calibration process before the system can be utilized (e.g. Krumm et al. (2000)). This means that recalibration is required every time the setup is moved. Depending on the system, this can require a huge amount of time and an expert to perform the process. Since the goal is to design an integrated tabletop tracking system that can be easily moved together with the table, the system should require no calibration.

- **Independence from External Influences**: With mobility comes another requirement: due to the different locations in which tabletops are set up, the tracking system should be able to adapt to changing external influences. Such influences and differences can become manifest in both tangible (e.g. different architecture of the surrounding room) and intangible ways (e.g. different lighting conditions).

- **Robustness**: This last requirement is also linked to the need for mobility. The tracking system should be as robust as possible, such that the chance of damages during the process of assembling, disassembling and moving the table are minimized.

In order to implement such a tabletop-integrated tracking system, one can think of multiple hardware design alternatives. Nitsche (2011a) elaborates on four such alternatives: rotational laser measurement, pressure sensitive floor mats, overhead range cameras and distance sensors. Each approach comes with its own advantages and drawbacks. Table 1 summarizes how well these approaches fulfill the previously mentioned requirements.

Based on this evaluation, the tracking system was implemented using an array of infrared (IR) distance sensors. The idea of detecting users around a tabletop via proximity sensors was first published by Walther-Franks et al. (2008). The authors provide multiple application scenarios for utilizing a user tracking system in both single and multi-user settings. However, the proposed system has not been implemented so far. In the following sections, the implementation of such a tracking system will be described in further detail.

4.2 HARDWARE IMPLEMENTATION

The hardware foundation of the tracking system is an Arduino Uno microcontroller board. Arduino is an open-source electronics platform[2] that primarily aims for the design and implementation of interactive objects and environments. The foundation of each Arduino project is one of the Arduino I/O (input/output) boards. These boards usually consist of an Atmel megaAVR microcontroller[3], a serial to USB converter and a number of analog and digital in- and outputs. The programming language in use is a simplified subset of the C standard library. The inputs of an Arduino board can be used to connect a variety of sensors and direct input devices like physical buttons and sliders. On the output side, the possibilities are multitudinous since every device that can be controlled digitally can serve as a potential output device.

In order to detect the presence of a user at the table, the tracking system employs an array of IR distance sensors[4] with a measuring range of 20-150 cm. Before a first prototype of the tracking system could be built, it was necessary to find out how the sensors should be distributed around the table in order to allow for adequate tracking results. Therefore, some initial experiments with a small test setup were conducted. These tests revealed that a user, when located directly in front of the table, should at least cover four sensors at any time in order to allow for a functional and robust tracking.

Based on the table's measurements, the sensor array requires a total of 80 distance sensors. However, the Arduino board supports a maximum of only six analog inputs. Therefore, it is required to connect multiple sensors to a single input by employing multiplexers. A multiplexer is a multiple-input, single-output switch used to serialize multiple inputs into a single signal. The tracking system is equipped with six 16-channel multiplexers[5]. By applying a parallel wiring, it is possible to connect all 80 sensors to a single analog input of the Arduino board.

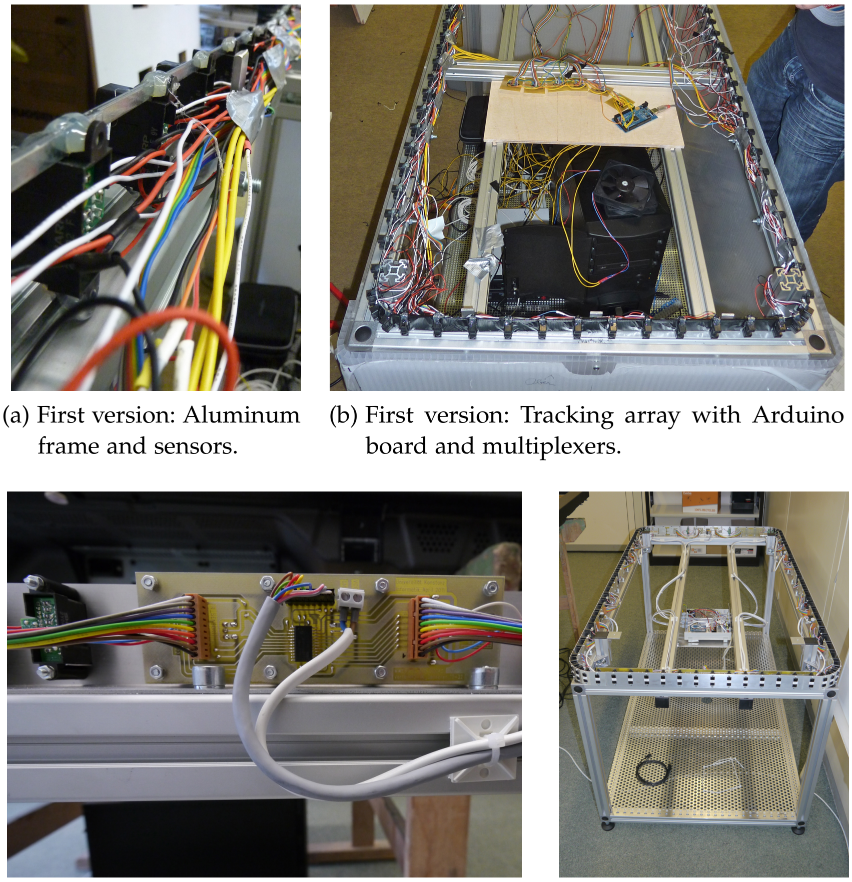
The first version of the tracking system was drafted and built by members of the "Blended Museum" team of the HCI group at the

2 http://www.arduino.cc – Arduino website. Last accessed 2012-02-04

3 http://www.atmel.com/dyn/products/devices.asp?category_id=163&family_id=607 – Atmel megaAVR series microcontrollers. Last accessed 2012-02-04

4 http://sharp-world.com/products/device/lineup/data/pdf/datasheet/gp2y0a02_e.pdf – Sharp GP2Y0A02YK sensor specifications. Last accessed 2012-02-04

5 http://www.ti.com/product/cd74hc4067 – Texas Instruments CD74HC4067 MUX specifications. Last accessed 2012-02-04



(a) First version: Aluminum frame and sensors.

(b) First version: Tracking array with Arduino board and multiplexers.

(c) Second version: One of the sensor modules.

(d) Second version: Tracking array.

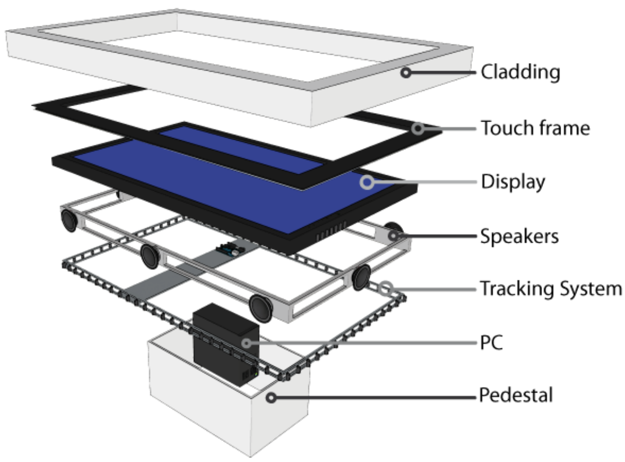
Figure 5: Two versions of the tracking system's sensor array.

University of Konstanz [6]. It is based on a two-railed rectangular aluminium frame, to which the sensors are attached with hot-melt adhesive (Fig. 5a). The sensors are distributed along the frame as follows: 22 sensors on each of the long edges, 12 sensors on each of the short edges, and 3 sensors at each corner (Fig. 5b. At the time of writing, this implementation has been in use in a public exhibition for over one year without any malfunctioning or any need for service (details of the exhibition follow in chapter 5). It may therefore be considered as a proof of concept for the reliability and robustness of such a system in a real-life context.

A second, improved version of the tracking system has been built at the scientific workshops of the University of Konstanz (Fig. 5d). This implementation uses 96 sensors, thus increasing the system's accuracy. The sensor array is implemented as a set of independent modules. Each module is based on a metal bracket that carries multiple sensors, a printed circuit board, a multiplexer and two plug-in connections

6 http://hci.uni-konstanz.de/BlendedMuseum – Blended Museum project website. Last accessed 2012-03-04.

Figure 6: Construction layout of the multitouch table



in order to connect to adjacent modules (Fig. 5c). In this way, the alignment of the sensors is more stable compared to the first version. Furthermore, it is easier to replace single sensors in the event of a malfunction.

The tracking system is integrated into a multitouch table that is depicted in Figure 6. It is based upon a Panasonic TH-65 PF plasma display [7] with a size of 65″ and full HD resolution (1920px * 1080px). The system can be controlled via touch input by means of a Citron dreaMTouch MTIR 650W infrared touch frame [8]. This frame can detect up to 32 simultaneous touches at a rate of 50 Hz. The display as well as the touch frame are connected to a high-end PC located within the table's pedestal. A further special attribute of the table is that it uses eight speakers that are distributed along the four table edges and that are integrated into the cladding. By means of the PC's 7.1 surround sound capability, each speaker can be addressed separately. In combination with the tracking system, this means that the system can provide targeted audio feedback at a user's location.

4.3 Software implementation

The Arduino board used in the tracking hardware is powerful enough to provide a high frequency of sensor readings, thereby providing sufficient temporal resolution for an accurate tracking. However, it

7 http://panasonic.net/prodisplays/download/pdf/specsheet/TH-65PF11RK.pdf – Panasonic TH-65PF plasma display data sheet. Last accessed 2012-03-04.
8 http://www.citron.de/index.php?id=127&L=3 – Citron dreaMTouch product site. Last accessed 2012-03-04.

is not powerful enough for executing advanced tracking algorithms. Therefore the tracking software is divided into two parts, which will be described in the following sections. One part is the Arduino software, which reads data from the sensors and serves as a serial data provider for the raw tracking data. The second part is a WPF/C# application, which uses this data to generate high-level tracking objects and events.

4.3.1 *Arduino Data Provider*

The main task of the Arduino board is to successively read the current distance measurement of each sensor and send it to its serial output as a combined string. Even though the sensors can measure an exact distance to the nearest object, the tracking system does not make use of this option due to the following reasons: firstly, the maximum range of the sensors is very limited. Implementing a meaningful system response or interaction paradigm based on distance is therefore hardly useful. Secondly, distance sensors do not provide perfect data: lightning conditions, different materials and variation in voltage can lead to imprecise and fluctuating measurements. Hence, the tracking system defines a single distance threshold and provides binary data for each sensor based on this threshold: if there is no object within the threshold distance, the sensor value is 0, otherwise 1. The aforementioned fluctuations are smoothed by employing a median filter. Median filters are insensitive to outliers and especially useful for the removal of impulsive noise (Vaseghi, 2009, 350), as it was sometimes observed for the sensors during the hardware test phase.

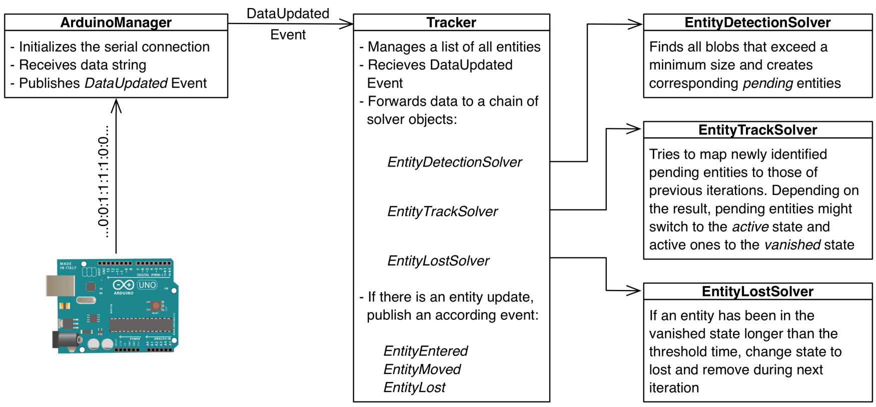
In this way, the Arduino sketch collects the measurements for all connected sensors and concatenates them into a string, which is then published via the serial port. At the other end of the serial connection, a WPF/C# application receives the data and forwards it to the tracking software, which is described further in the next section.

4.3.2 *WPF/C# Tracking Software*

Figure 7 shows an overview of the entire tracking process and its components. When data from all sensors has been collected by the Arduino board, it is sent to the PC via serial connection. The *ArduinoManager* object manages this serial connection and receives the raw tracking data. Upon reception it raises the *DataUpdated* event, which encapsulates the raw data. The *Tracker* object in turn listens to the DataUpdated event. As soon as new data is available, the data is channeled through a chain of solvers, which do the actual tracking. Finally, the Tracker object publishes events for the appearance, movement and disappearance of recognized objects.

The core tracking functionality is contained in so-called *Solver* objects. Each Solver is responsible for a subtask of the tracking process

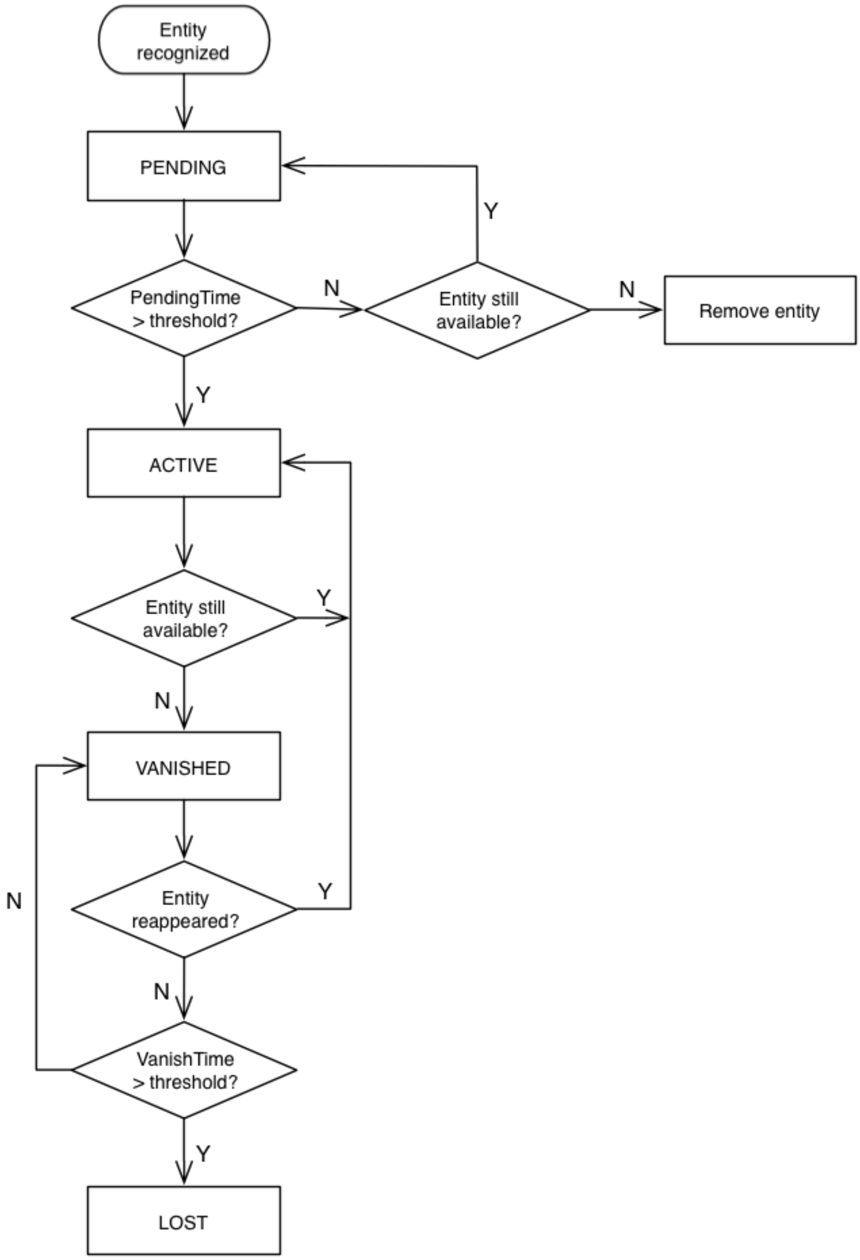
Figure 7: Overview of the entire tracking process and its major components



and can work with both the raw tracking data as well as with the output of previous solvers and/or previous iterations. There are three different solvers with the following responsibilities: detecting new objects (*EntityDetectionSolver*), tracking movements (*EntityTrackSolver*), and disposing objects that no longer exist (*EntityLostSolver*). A detailed description of the underlying algorithms can be found in (Nitsche, 2011a, pp. 22 et seq.).

Tracked objects are internally represented as so-called *Entities*. Each Entity has a position, represented as normalized x/y coordinate, a size, and a state. In order for an entity to be considered, it needs to exceed a minimum size. The size of an entity is defined as the number of directly adjacent sensors that sense an object. Each entity has one of the following states: *PENDING*, *ACTIVE*, *VANISHED* and *LOST*. Figure 8 shows the lifecycle of an entity and how the transitions between the different states are defined. The intermediate states of PENDING and VANISHED have been introduced in order to avoid oversensitive responses of the tracking system. The PENDING state makes sure that an object exists for a minimum time span before it is considered in order to minimize the chance of reacting to temporary objects such as people that walk by the table. The VANISHED state, on the other hand, avoids premature disposal of objects that have disappeared for a short time, for example because of false sensor readings. Based on this entity lifecycle, a robust and steady tracking system could be implemented.

Figure 8: Overview of the entity lifecycle



5 APPLICATION IN A MUSEUM ENVIRONMENT

The multitouch table presented in the previous chapter was utilized during a public long-term exhibition on the history of German telephony. General information on this exhibition will be covered in the first section of this chapter. Afterwards, two applications that were deployed during the exhibition will be presented. Here, the focus is on the integration of the tracking system into the application's interaction design.

5.1 THE EXHIBITION SCENARIO

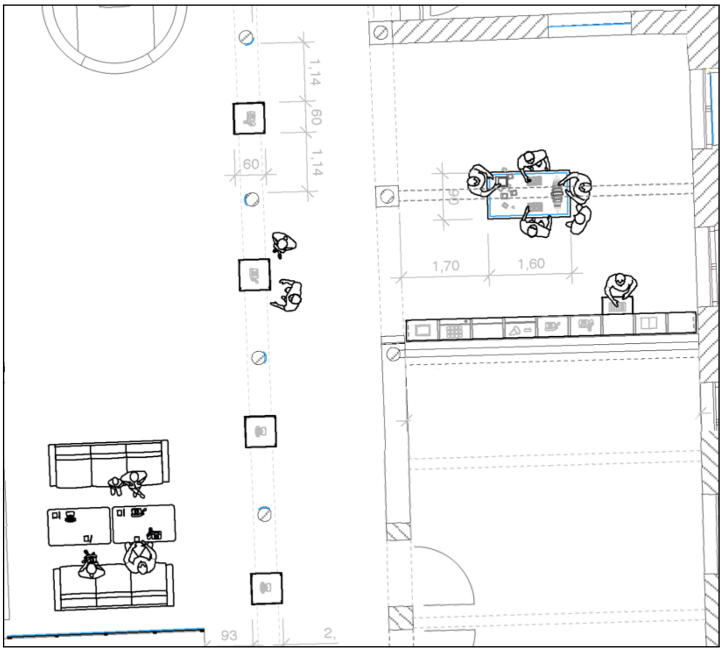
„Fernbeziehung – Eine Ausstellung über den Nutzen und Nachteil des Telefons für das Leben" (metaphrase „Long Distance Relationship – an Exhibition on the Benefits and Drawbacks of the Telephone for Life") is the title of an exhibition that takes place in a public bank building in Konstanz, Germany from September 15th, 2010 until February 27th, 2012. The exhibition is based on the Schmidt Collection[1], which is a private collection that embraces nearly the entire history of German telephony up to the 1990s.

The exhibition is spatially divided into three parts: a column of showcases, an audio lounge, and a wall-size display case cabinet (Figure 9). Since the labeling of the single exhibits is very brief and most often consists of name and year only, deeper information needs to be conveyed in another way. This is the purpose of the multitouch table, which can be regarded as the central information hub of the exhibition. Here, multiple users can simultaneously access supplementary information about each exhibit. Various media types (text, image, audio, video) are employed to present the diverse contents. The table is located in a separate open area of the bank building opposite to the display case cabinet, and is placed such that it can be accessed from all four sides.

The exhibition is also divided into three time periods, where each period comes with its own main theme and corresponding exhibits. The application running on the multitouch table as well as its contents were also exchanged for each period. In the following section, the two applications used during the first two exhibition periods will be presented in more detail.

1 http://www.sammlung-schmidt.de – Website of the Schmidt Collection (German). Last accessed 2012-03-04.

Figure 9: Plan of the exhibition showing the row of showcases, audio lounge (bottom left) and the multi-touch table with the display cabinet on the wall.

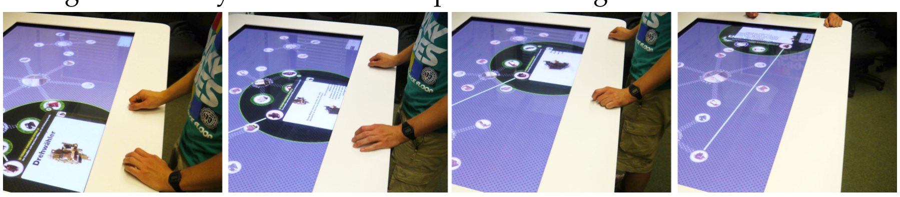


5.2 THE MUSEUM APPLICATIONS

5.2.1 *Goals of the Application*

The main objective of the museum application is to allow visitors to browse and explore the available information on single exhibits. This exploration process shall be supported in such a way that multiple users can interact with the tabletop in parallel without interfering with each other. Since there will be visitors with no previous experience of touch devices, the interaction design should motivate visitors to use the system while at the same time keeping the required operations as simple as possible (Klinkhammer et al., 2011).

Figure 10: A Dynamic Personal Space following a user's movements.



These objectives will be approached with the concept of dynamic personal spaces (DPS). A DPS is a visually distinct area that is bound to a users position and resembles her working area. It can therefore be considered as a virtual representation of the personal territory as defined by (Scott, 2003, 18). A DPS is considered dynamic because it is

Figure 11: Screenshot of the first application, showing two personal spaces with expanded information items.

controlled by the presence of the visitor. When the visitor approaches the table, a DPS will appear directly in front of her. As the visitor moves around the table, the DPS including its current content follows her (Figure 10). After a visitor has left the table, the DPS will disappear. In this way, a DPS can serve multiple purposes. Firstly, it can act as a lure that motivates users to interact with the system. The dynamic and user-centered response of such a system is rather unusual and might therefore evoke interest and ultimately lead to a deeper engagement with the system (Klinkhammer et al., 2011). Secondly, DPSs allow for adaptive user support. If the system recognizes a user who has not been interacting, it can automatically provide some kind of support and thus assist the user during her first steps. Finally, DPSs can support parallel exploration on equal terms because the visual borders of a DPS automatically lead to a partitioning of the table surface. Based on this concept, two different applications have been implemented. These applications will be described in more detail in the following sections.

5.2.2 *Exhibition Application I*

The user interface (UI) of the first application consists of three major elements: a public space, multiple DPSs and multiple information items. Figure 11 shows a screenshot of the application featuring all these elements. The public space is the main area of the UI and takes the entire screen. It contains the so-called information items, which are iconic representations of the single exhibits. Information items are free-floating within the public space and are animated with the help of a physics engine. Therefore, information items have physical properties like acceleration and inertia. They can also collide with

Figure 12: Dragging an information item into the DPS

each other and be attracted or repelled by force fields. The items in the public space are not ordered but move around continuously due to a large circular force field.

The DPSs are tightly fixed to the tracking system (see above). Upon arrival of a user, a new DPS slides into the public space from the edge directly in front of her. Their visual design resembles a semi-transparent rotary phone dial in order to match the exhibition's theme. The slots in the rotary dial serve as bays into which the user can drag information items.

User interactions can occur within the public and the personal space. In the public space, users can drag and flick the information items freely. This leads to a rather playful interaction that does however not convey deeper information. In order to access detailed information, information items have to be dragged and dropped into a DPS slot. As soon as an item is added, it becomes active and unfolds its contents (Figure 12). When adding another item to a free slot, the active item is minimized and the new item is opened. Users can access other items that are contained in their DPS by rotating the dial. When activating an information item, it unfolds one or more facets, which are represented as speech bubbles. Each facet stands for a certain aspect of an exhibit. The currently active facet is centered above the DPS. Inactive facets are reduced to small speech bubbles that can be selected by tapping them. Within those facets, users can interact depending on the contents, e.g. flipping through a slide show or scrolling through text.

5.2.3 *Exhibition Application II*

The second application (Figure 13) is similar to the first one concerning the major elements: it also features a public space, DPSs and information items. In this version, information items are not floating around the public space freely. Rather than that, each item is assigned to one of three topical clusters. Each cluster center is represented as a large static bubble, and all information items that belong to this cluster are animated carousel-like around it. In order to further emphasize the connection between a cluster center and its members, a visual link is displayed between them.

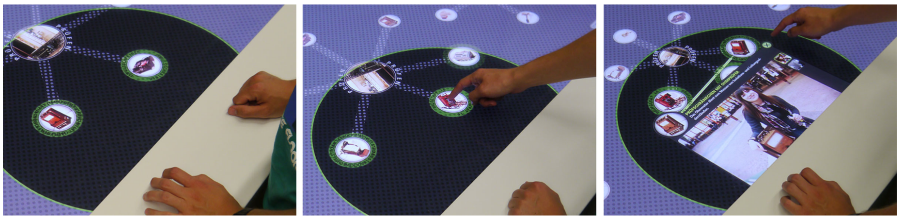
Figure 13: Screenshot of the second application, showing two personal spaces with opened information items.

The DPSs have been increased in size and received a new visual design. They are now displayed as accentuated ellipses that provide a user-centered view onto the group space. The goal of this visual redesign was to make the DPS more prominent and easier to recognize. Furthermore, while the DPS in the first version resembles a widget on top of the application, the new DPS design suggests a lens through which the user is looking onto the group space. This effect is increased by adapting the behavior of the information items: when an information item moves into a DPS, it is automatically highlighted in order to attract the user's attention.

Further changes have been implemented concerning the interaction paradigm. In the first part, users could open information items by dragging and dropping them into their DPS. This approach was dropped in favor of a simpler technique. Whenever an information item is within a DPS, it can be opened with a single tap (Figure 14). Alternatively, users can also drag items from the public space into their personal space in order to open them. In doing so, it was possible to introduce an easier selection process for new visitors whilst still supporting the drag and drop approach, which might be applied by visitors that have used the first application before. Furthermore, there are no more facets such that each information item comprises only a single content element. In this way, the the UI design could be further simplified.

After introducing the two museum applications including their interaction design, the next chapter will focus on the evaluation of the DPS approach. The first section will evaluate the two museum applications based on the logging data that has been collected throughout the exhibition. It will also include a comparison of the two applications and analyze how the different interaction designs influenced

Figure 14: Opening an information item with a single tap.



the users' behavior. Thereafter, a laboratory study will be presented which studies the fundamental motives and conditions that underly user's movements around an interactive tabletop. It will also examine if and how the DPS approach influences user's strategies during collaboration and competition.

6 RESULTS FROM AN IN-THE-WILD SETUP

The multitouch table presented in chapter 4 was utilized during a long-term exhibition on the history of German telephony. The exhibition scenario as well as the applications that were used during the two different exhibition periods are described in detail in chapter 5. Throughout the exhibition, interaction logging was applied in order to collect quantitative data from the users. Due to the usage of dynamic personal spaces, it is possible to assign interactions to specific users (Nitsche, 2011b). Therefore, the data can be analyzed on a per-user basis, including the location and movements of the users. The following sections address the scenario in which the table was used as well as the results that were derived from the logging data.

6.1 DATA COLLECTION AND DATA CLEANING

The data presented in the following sections has been collected over two time periods. The first period started at September 15th, 2010 and showed the first application (see chapter 5.2.2). However, since the tracking system was not fully operational at that time, data collection did not begin before February 2nd, 2011 and ended March 28th, 2011. The second part employed the second application (see chapter 13) and took place from April 18th, 2011 to October 4th, 2011. Opening hours of the exhibition were Monday to Friday, 8.30am to 4.30pm except Thursdays, where it closed at 6.30pm. Since the exhibition was closed on weekends and public holidays, this makes 39 days of data collection for the first part and 116 days for the second part.

The following section will mostly rely on the term *session*. A session starts as soon as a personal space is displayed and ends when it is disposed. This happens 2.5 seconds after the tracking system has lost the user. Therefore, the actual duration of a session is the time between start and end minus 2.5 seconds. Due to this implementational detail, the data has been cleaned in the following ways:

- All sessions with a duration of 3 seconds or smaller are not considered: subtracting the 2.5 second time delay of the tracking system, only 0.5 seconds of active session time remain. These sessions are considered as null-sessions and are therefore not included in the analysis. Such short sessions might for example occur when a person is walking by the table.

- For the remaining sessions, the session duration will be the time between between start and end minus 2.5 seconds in order to better reflect the actual time of presence of a user

When looking at the data that follows, one will realize that the variance within the data is extremely high in nearly all of its dimensions. It is assumed that this can be attributed to the context of the exhibition. As previously mentioned, it takes place in a public bank building. This means that there are two potential high-level user groups: visitors of the exhibition and bank customers. Whereas exhibition visitors access the table because they are interested in the topic, bank customers might do so simply because they are waiting to be served and therefore saunter around the exhibition space. It is obvious that these two user groups have very different goals and intentions, which are also reflected in their interactions with the multitouch table and ultimately in the logging data.

It would be possible to clean the data by identifying and removing outliers. However, before removing outliers one should consider where these extreme data sets come from. Osborne and Overbay (2004) names multiple potential sources of outliers, for example sampling errors or data errors during data entry, recording or collection. Another source of outliers however may also be that the outliers are actually valid samples of the correct population. Since all data from the exhibition has been collected by a single computer system, without any human influence, and without any known breakdowns or malfunctions, it is assumed that all samples are actually valid and the variance of the data is due to the previously mentioned context of use. Still the question is how to manage outliers. Orr and Sackett (1991) conducted a survey amongst 100 researchers that published work in the field of organizational psychology in order to assess how they deal with outliers and which detection techniques they apply. The survey revealed that 67% of the respondents would remove data only if there is an evidence for their invalidity. Another 29% include all data points regardless of outliers. Finally, only 4% claimed that the extremity of outliers is by itself a reason for removing them. Based on these insights, the data from the exhibition will be analyzed as it is and without removing any extreme data points. Even though this might prevent statistically significant results, it is considered the right approach since no other cause for erroneous data could be identified. Therefore all data points have to be considered as valid.

6.2 General figures

A total of 4524 sessions were recorded during the exhibition, with 1712 sessions for the first part and 2812 for the second. Applying the restriction on minimum session time mentioned above results in the following figures: 4320 sessions in total (minus 204 sessions, 4.72%

Table 2: General data on the two exhibition parts based on interaction logging

Metric	Part 1	Part 2
# of sessions	1446	2415
# of bystanders (%)	748 (51.73%)	1148 (47.54%)
Avg duration (SD)	84.78s (165.99)	111.28 (222.27)
Min / Max duration	1 / 1894	1 / 3139
Avg # items added (SD) [without bystanders]	13.65 (64.83)	9.72 (33.26)
Avg time to first item added (SD) [without bystanders]	34.43s (98.46)	20.30 (44.42)
Avg # of interactions per minute (SD) [without bystanders]	6.19 (3.86)	4.70 (2.74)

removed), 1636 for part 1 (minus 76 sessions, 4.65% removed) and 2684 for part 2 (minus 128 sessions, 4.77% removed). Before looking at some general figures, some more datasets need to be removed temporarily in order to get more representative data. This is due because there were some special events that took place during the exhibition, namely opening and closing events of the single exhibition parts. During these events, many people were gathering tightly around the table for a long time. Unfortunately, the tracking system cannot provide accurate data in this case: since new users took over the PSs from departing users in an instant, the system could not detect session start or end events. The resulting log files therefore contain only a small number of sessions that do however have a very long duration and a very high number of interactions. Since this data can be clearly identified as incorrect, it will be ignored for the analysis of general figures. As a result, these figures are based on 3861 sessions (minus 459 sessions, 10.64% removed): 1446 session for the first exhibition part (minus 190 sessions, 11.61% removed) and 2415 for the second (minus 269 sessions, 10.02% removed).

6.2.1 *Comparing the Two Applications*

Even though the data is distributed so widely, some quantitative insight could be gathered based on the logging data. As described earlier, the two systems employ different interaction techniques for adding information items: drag and drop (first part) and tap to open (second part). An indicator that allows to compare these two approaches might be the time it requires a user in order to add the first item. As table 2 reveals, this time is on average about 14 seconds lower for the second part. A statistical analysis reveals that this effect is significant [$F(1,1796) = 17.528$; $p < .001$]. Because we expect the visitors and their behaviors to be comparable in both exhibition settings, we can assume that the tap to open approach has been adapted more easily. This makes sense because it is simpler than dragging and dropping an item. This outcome suggests that public systems should provide entry points that are easy to understand such that users can start interacting right away.

The success of using the interface might be reflected in the time a user spends with a system. The statistical analysis of session durations revealed that for those people who did interact with the system, session duration was significantly higher for the second application [$F(1,1796) = 5.428$; $p = .020$]. Even though this is no clear indicator of usability (remember that the contents presented were also different), one might argue that usability plays a factor in the time spent with a system, amongst others.

There is also data available on the average number of interactions per minute carried out by the users. However, these data sets cannot be compared meaningfully because the two applications contain different types of information items. The first part used a vide variety of items that included videos, slideshows, 360-degree views and a quiz, to mention a few. The second application however mostly relied on videos and a small amount of slideshows. Since a video does not require many interactions, it is clear that the average rate of interactions is lower for the second part. But as already mentioned, comparing these values in this place does not make sense.

Information on user interactions is just one aspect... tracking system.. movement data

6.3 User Movements and Spatial Patterns

This section will deal with the movements of users and the spatial patterns that occur when people gather around multi-touch tables. Firstly, the movement of users in general will be analyzed in order to find out if visitors are moving around the table and if so, to what extent they do so. After that, the spatial patterns that occur when one or more visitors stand at the table are analyzed. The data used in this section relies on the entire logging data, including the data that was collected during the previously mentioned special events.

6.3.1 *User Movements*

An analysis of movement data has revealed that on average, a user moves 0.79 times the distance that corresponds to the long edge of the table (SD 0.89). This is a distance of approximately 137cm. As with all the other data, the distribution of values is very wide. Furthermore, the data does not tell us under which conditions and with what kind of intentions these movements occurred. However, one can see that users do seem to make use of the tracking system in some way.

One factor that might influence the data positively is that the tracking system is a novel technique. Observations revealed that visitors were often stunned because the table "knew where they are". Many times, visitors were looking around in order to search for a camera. Other visitors tried to analyze the tracking system by first waving their hands, then moving their feet. Due to this experience, it might be assumed that some visitors were walking around the table intentionally in order to test and play with the tracking system.

Because of this unpredictable influence, and because the logging data can not convey much information without any contextual information, the detailed analysis of user movements will be conducted in an experiment which is described in chapter 7.

6.3.2 *Spatial Patterns*

Besides the movements of individual users, one can also look at spatial patterns and arrangements that occur when one or more users are gathered around the table. In order to derive these patterns, the space around the table is divided into multiple zones. Each user position is assigned to the zone within which it lies. A problem that occurs when applying this technique is that the borders between zones are hard and membership to a zone is therefore binary. This is an unfavorable solution because a user standing close to a zone's border still belongs only to this zone, whilst the neighboring zone is considered empty. Therefore, the user arrangements were analyzed by applying methods from fuzzy logic[1]. A fuzzy controller was implemented which can assign a single user to multiple zones depending on the user's location. The fuzzy controller uses a trapezoidal membership function because it is effective yet simple to implement. The fuzzifier has been chosen such that two neighboring zones overlap by 10%. This means that the core of a zone where the membership degree is 1 takes 80% of the zone's width. All positions within the "left and right" 10% of a zone will be assigned to two zones with different membership degrees. The controller has been implemented such that the fuzzifier as well as the number of zones per short edge and per long edge can be changed dynamically. Furthermore, since all zones use the same fuzzifier, the sum of all memberships for a single user position is always 1. In this way, a more appropriate representation of user positions that considers the imprecisions of the real world can be achieved.

The spatial patterns are based on a fuzzy controller with three zones per long edge and three zones per short edge. This does mean that zones on the short edge have a different size than zones on the long edge. This difference is however unimportant for the analysis. Three zones were chosen because it makes sense to distinguish if a user is located at the center or towards one of the corners of an edge. Therefore, at least three zones are required. Furthermore, the number of zones should be odd such that there is a central zone. This is a

1 For more details on fuzzy logic see for example Berthold and Hand (1999, ch. 9)

practicable approach since one might expect that users prefer central locations over others. In order to make the size of the long edge and short edge zones approximately equal, an alternative would have been to use three zones on the short edge and five zones on the long edge. However, due to the tables measurements, segmenting the long edge into five parts would not make much sense. Furthermore, this setup would result in a total of 16 zones. With so many zones, it is hard to recognize recurring patterns because the possible combinations of zones for multi-user settings is extremely high. Due to these reasons, each table edge was divided into three zones.

Figure 15 shows the most common user distributions for different numbers of users[2]. The images are aligned such that the showcase, which was located in the same room, is to the bottom. The entrance to the room is to the left. In the following, the identified patterns will be analyzed in more detail.

Single User Patterns

The single user patterns (2673 sessions) do not reveal any surprising insights. Taking into account that users will most probably approach the table from the left (entrance) or from the bottom (showcase), the resulting distribution seems more than reasonable. A total of 72.24% of users entered the table from these main directions.

Patterns for Two Users

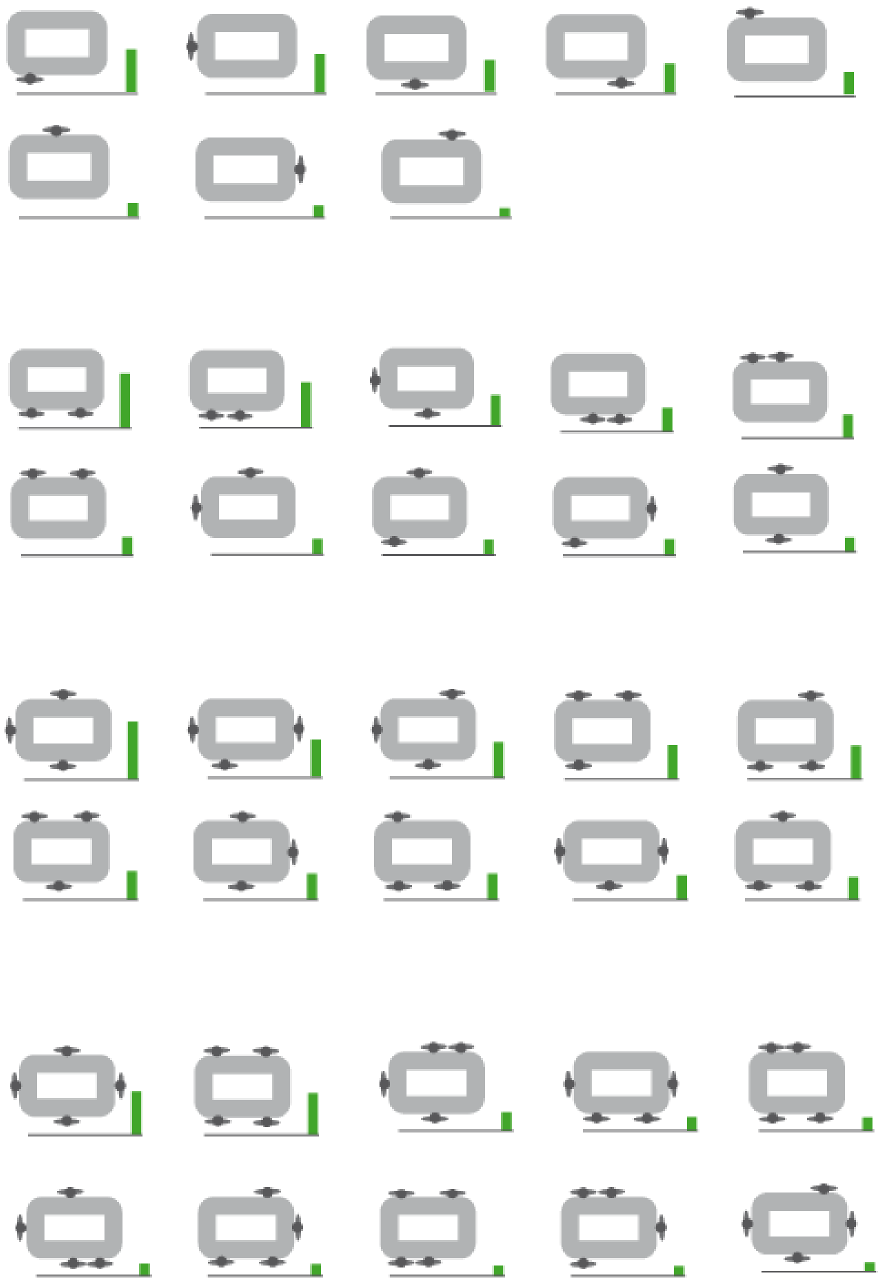
Looking at the distribution of patterns for two users (1157 sessions[3]), a vast majority users are located side by side (41.56%). This arrangement is followed by around-the-corner patterns (15.69%) and opposite patterns (7.55%). It is interesting to see that the side by side arrangement is so predominant because according to Sommer (1965) (see also Figure 4), this arrangement is usually most prevalent in cooperation. For co-acting, which one would expect to be the most important task type in the given scenario, Sommer mentions diagonally opposite arrangements as the most common. However, the exhibition data shows that this arrangement only occurred to a small fraction (4.05%). Another striking aspect is that all the around-the-corner arrangements are distributed such that visitors stand at some distance from each other.

The reasons why these patterns differ so much from these analyzed by Sommer are unclear. However, there are multiple explanations that should be considered. Firstly, Sommer conducted his study using a questionnaire, asking participants to mark their preferred seating location for a given task. One might argue that the result of such a

2 Please note that this figure only shows to ten most common patterns. Therefore, the sum of percentages referred to hereafter is not 100%.

3 Please note that the sum of sessions does not represent the visitor statistics, since a single person can play a role in multiple group sizes.

Figure 15: Frequency of the ten most common spatial distribution patterns for different numbers of users.



questionnaire does not entirely represent reality. When approaching a table, multiple factors can influence the decision on where to stand. On the one hand, there are hard facts like the user's goal, the direction from where she is coming or the space available. On the other hand, soft factors do also play a role. Do I know the person standing at the table, and if yes do I like her? Such social and cultural issues certainly have an impact on the preferred location. Another argument may be that standing at a table and sitting at a table are two different things that lead to different arrangements. These are some of the factors that might influence standing preferences at a multi-touch table, not only for settings with two users but also for more.

Patterns for Three Users

There were 399 sessions with three concurrent users. One can distinguish two general types of arrangements in this group: such with users occupying three sides of the table (25.68%), and such occupying only two sides (20.33%). The three most-preferred arrangements are all three-sided. This might be due to the fact that such a configuration provides the highest degree of freedom for each user, since every user is occupying her own side. This effect could also be explained with territoriality: A user located at one edge of the table, especially when standing in the center, might be perceived as the "owner" of that edge and therefore, a further person approaching the table selects an unoccupied edge. One can also see that in most configurations, two users are standing directly opposite to each other. Such an arrangement might be most probable for people who know each other because it provokes eye contact, which is usually avoided by strangers.

Patterns for Four Users

A similar distinction as employed for the patterns for three users can be made here, namely how many edges of the table are occupied. There are arrangements occupying four (15.88 %), three (19.34%) and two (23.18%) edges. The two most common configurations are symmetric and equally distributed, with the most common one being one user per edge. As with the three user patterns, the degree of freedom of a user as well as an adapted theory of territoriality could account for this pattern. The configurations are based on data from 188 sessions.

Even though the tracking system allows up to six DPSs, patterns with more than four users will not be analyized here. Due to the table's size, there are not very many options for such a large group to arrange in different patterns. Furthermore, the number of sessions with five and six users respectively was very low and the differences between single configurations were marginal.

6.4 SUMMARY OF RESULTS

This section provided a number of insights. First of all, we have seen that a low entry barrier for a public system should be one of the major design goals. Even such a seemingly trivial difference as drag and drop versus tap can already have a noticeable effect. Especially for public systems, it is crucial to provide easy to use entry points to the user. Otherwise, people will probably loose interest in a system rather quickly.

The analysis of movements around the table has revealed that people seem to make use of the tracking system. However, because these insights are based purely on logging data, one can not know the goals and conditions underlying these movements. This issue will therefore be further illuminated in the next chapter.

Finally, the spatial arrangement patterns provided comprehensive data for analying common patterns that occur in public settings. These pattern have revealed that the seating arrangements for different task types as proposed by Sommer (1965) do not always hold. A number of factors that could influence the configuration of users around an interactive tabletop were identified. In the next chapter, an experiment that aims towards basic properties of DPSs in group settings will be conducted and evaluated.

7 EVALUATION IN THE LAB

The evaluation of the exhibition data has revealed that visitors actually do walk around a multi-touch table, and therefore make use of the tracking system even though they would not have to. A self-regulating process that is mediated by the DPSs has also been observed. Finally, the data has revealed that different (interaction-) designs of a DPS do influence the usage of such a system. However, all of the logging data has been collected in absence of a researcher who could observe the behaviors of users and their causes. Furthermore, the system at the exhibition is designed for parallel interaction and not for group work. Nevertheless, collaborative work is one of the most interesting scenarios for DPS. It is also unclear if and how group members would make use of a DPS whilst working together. Therefore, an experiment that addresses these issues has been conducted in addition. The following sections will describe the goal and setup of this study and provide some interesting results and analyses.

7.1 GOAL OF THE STUDY

The analysis of logging data from the exhibition has revealed that users seem to make use of the tracking system because they move around the table. However, nothing is known about the conditions under which this behavior occurs. Therefore, this study is focused on the fundamental motives, goals and conditions that underly user's movements around an interactive tabletop. The application of DPSs is especially interesting in group settings where users are either collaborating or competing (group work) instead of working in an unrelated, detached and parallel way (co-located work). Consequently, the study will be based on group tasks that require either collaboration or competition.

In this context, the study will also look at the strategies employed by single users as well as by the entire group in order to find out if and how these strategies are influenced by the DPS approach.

7.1.1 *Operationalisation*

In order to assess if DPSs evoke different behaviors concerning user movements and what conditions underly these behaviors, the DPS approach needs to be compared to some kind of baseline. In order to maximize comparability between DPSs and the control condition, the two conditions should be as similar as possible. For that reason, this study will compare DPSs to static personal spaces (SPS). The visual and interaction design of the PSs in both conditions as well as the tasks provided to the participants will be identical, such that the only difference between the two conditions is that the PS will either follow a user (DPS) or remain at a fixed position (SPS).

Besides analyzing user movements and their causes, this study also wants to find out if DPSs influence the strategies applied by a group or by single users. This analysis will be conducted both in a qualitative and a quantitative way. The qualitative analysis focuses on the types of strategies employed and how these strategies evolve. The quantitative evaluation will be based on task completion time, which can be regarded as a quantitative measure for efficiency. In this way, the study can also reveal potential positive or negative influences that DPSs might have on the efficiency of a group.

7.1.2 *Research Question & Hypotheses*

As already mentioned, this study focuses on the basic influences of DPSs onto the behavior of single users and groups. Here, the focus is on the movement of users. It is assumed that the possibility of moving around a table with a DPS does by itself lead to an increased amount of movement. Stated the other way around, users that face a SPS will rather remain at the same location because the advantages of staying with one's SPS weigh stronger than the desire to move.

In order to examine this issue, the research question underlying this study is as follows:

> RQ: How does the application of dynamic personal spaces influence user movements around an interactive tabletop?

In order to answer this research question, the following hypothesis will be postulated:

> H_{A1}: The application of Dynamic Personal Spaces leads to an increased amount of movement.
> H_{A0}: The application of Dynamic Personal Spaces does not lead to an increased amount of movement.

Furthermore, two additional hypotheses will be postulated. These hypotheses focus on secondary effects that might be influenced by DPSs: interaction radius and the frequency at which users will lean over the table in order to reach an item. Because users are able to move in the DPS condition, it is assumed that both values decrease. Therefore, the following additional hypotheses are postulated:

> H_{B1}: The application of Dynamic Personal Spaces leads to a decreased interaction radius of users.
> H_{B0}: The application of Dynamic Personal Spaces does not

lead to a decreased interaction radius of users.

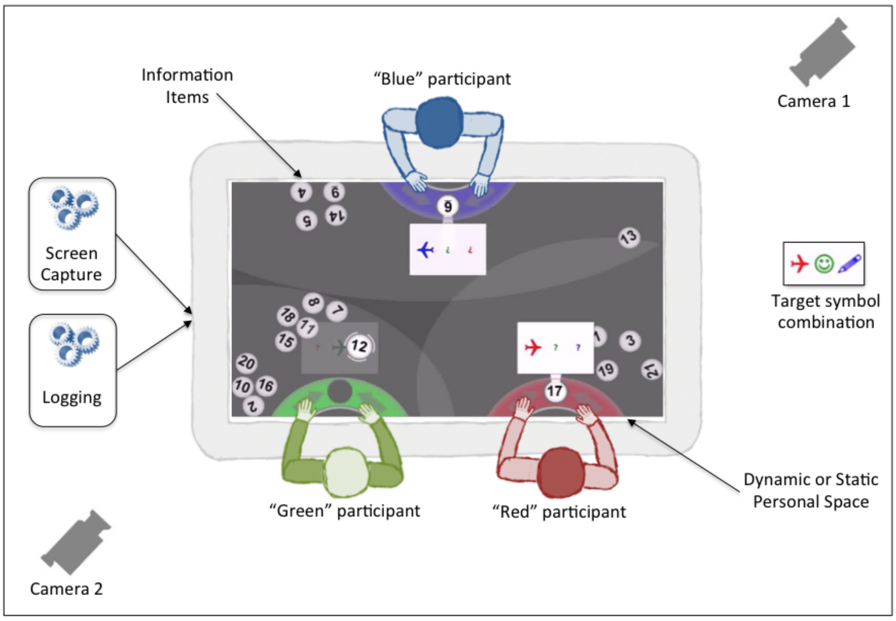
H_{C1}: The application of Dynamic Personal Spaces leads to a decreased amount of leaning over the table.
H_{C0}: The application of Dynamic Personal Spaces does not lead to a decreased amount of leaning over the table.

7.2 ORGANIZATION OF THE STUDY

The following sections will present a detailed description of how the study was organized. This includes the technical setup in the lab, the applied study design, the tasks that were assigned to the participants, and a description of the study procedure.

7.2.1 *Apparatus*

Figure 16: An overview of the study's setup and the user interface.



The experiment was conducted in a standard office room at the University of Konstanz. The multitouch table used in the experiment is identical to the one described in chapter 4. It was positioned towards the end of the room, such that participants could walk all the way around the table without any obstacles or constrictions. Besides the multitouch table, there were three PC workstations which were used by the participants to fill out the pre-test online questionnaires. Data from the experiments was recorded in several ways (see also Figure 16):

- Two HD cameras with wide-angle lenses were placed diagonally at some distance from the multitouch table's corners.
- The application used during the experiment was augmented with interaction logging
- A second PC was connected to the tabletop's secondary display output and recorded the tabletop's screen contents.
- Additional data was collected by the test supervisor through note-taking during the experiment.

7.2.2 *Study Design*

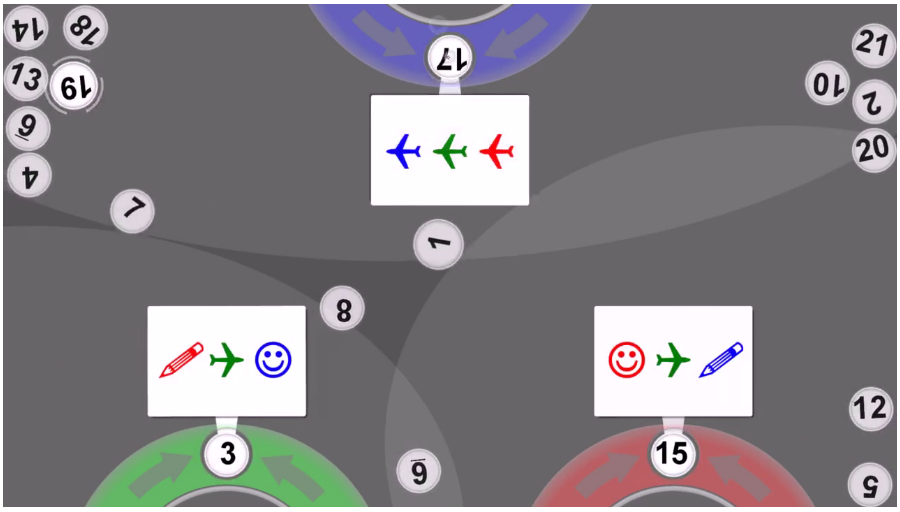
The study used a between-subjects design with personal space type as independent variable (dynamic vs. static PS). A between-subjects design was chosen for multiple reasons. First of all, using a within-subject design would allow participants to transfer their strategies from one system to another. Since strategies are one of the focal points of this study, this effect is not desirable. Another focal point is of course the movement and spatial arrangement of participants. Here, the transfer problem might occur again - participants that start with a dynamic PS might simply keep walking around the table even though their PS is static and vice versa. Besides, participants facing a static PS during one task and a dynamic PS during another may well become aware of the intention of the study. This might in turn lead to unnatural behavior due to the so-called *good-subject tendency*, which means that participants "act the way they think the experimenter wants them to act" (McBurney and White, 2009, p. 182). Therefore, a between-subject design was chosen.

The study was conducted as a group study with three members per group. The group size was mainly chosen based on the size of the tabletop in use. With this group size, participants have enough room to interact in parallel and walk around the table if desired, while conflicts concerning spatial arrangements (e.g. overlaps) or interactions on the tabletop (e.g. object ownership) might still occur.

7.2.3 *Tasks*

The experiment consisted of two different tasks, a collaborative one and a competitive one. The order of tasks was counterbalanced across all groups. The application employed during the experiment is based upon the application of the first exhibition part. There are 21 information items and three PSs. The PSs have been customized such that they can hold only a single item at a time. Furthermore, each PS has its own color (red, green or blue), which is used during the collaborative task described further below. The information items are labeled with

Figure 17: Screenshot of the competitive task where each participant can see all symbols.

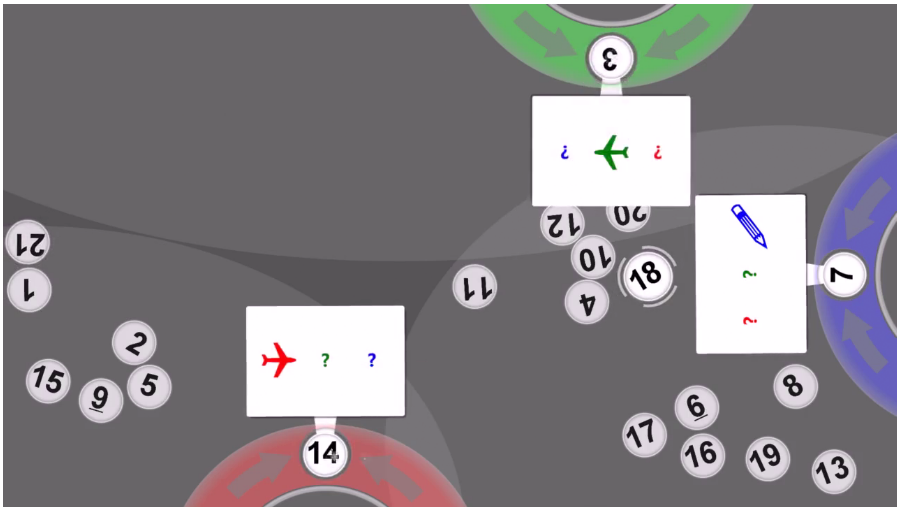


a distinct number between 1 and 21. When an item is added to a PS, it reveals its contents right above the PS. Each item contains three slots, where each slot has a distinct color: red, green and blue. Each slot contains a single symbol, which can either be an airplane, a pen, or a smiley. The symbols were chosen such that they can be easily distinguished both visually and verbally (in the German language). Thus, each item contains a combination of three differently colored symbols. Each color occurs only once, whereas the symbols might occur multiple times. Figure 17 shows a screenshot from the competitive task, featuring three different symbol combinations. At the beginning of a task, the items were arranged randomly on the table. In order to avoid a one-sided distribution of items however, the table surface was divided into four virtual zones with five or six randomly positioned items per zone. In this way, a non-uniform distribution of items that would provide an advantage to a single user because of her location could be avoided.

In the competitive task, an index card with a target combination of three colored symbols was presented to the participants. The participants' task was then to find the item that contained this combination. The first participant to find the target item received a point. In order to further motivate competitive behavior, the participant with the most points after 15 rounds received a chocolate bar. If two or three participants had an even score after 15 rounds, an additional round was started. Every five rounds the items were randomly rearranged within the group space. In this way unfair situations should be avoided, for example when a single participant managed to obtain and reserve a large amount of items after several rounds.

The collaborative task was similar in that there was also an index card with a target combination that needed to be identified. This time

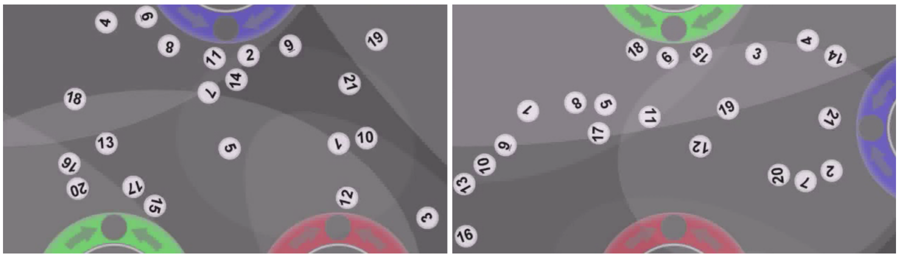
Figure 18: Screenshot of the collaborative task where each participant can only see one of the three symbols.



however, each participant could only see the symbol that had the same color as her PS. The other two symbols were replaced with question marks. An example screenshot of this setup can be seen in Figure 18. By allowing each participant to see only one of the three symbols, the group was forced to work together in order to identify the target item. As with the competitive task, there were 15 target items that needed to be identified by the group and all items were distributed randomly at the beginning of the task. Another similarity between the two tasks is that there was also a rearrangement of items every five rounds. This time, however, the intention of this procedure was not to avoid unfair situations. Instead, the periodical rearrangement of items was conducted in order to see if the group would stick to its previously agreed strategy or if they will dismiss it. Finally, the last target item of the collaborative task consisted of a symbol combination that did not exist. By adding this impossible task, it was possible to observe how a group changed its behaviors and strategies when their previous approach did not lead to a solution.

The two task types have been selected as they cover a wide variety of properties and require different strategies. The collaborative task requires a divide-and-conquer like strategy, since each group member needs to add the target item at least once in order to identify the right one. The competitive task on the other hand will probably rather lead to brute force strategies, where each member tries to add as many items as quickly as possible without paying attention to the others. One can also look at these tasks based on the Group Task Circumplex mentioned earlier (see Figure 1, p. 12). The competitive task used in this experiment is a type seven task (contests/battles/competition), which means that it is an executive task with behavioral and competitive qualities. The collaborative task is on the opposite side of

Figure 19: Predefined arrangement of SPS.



the circumplex because it is an intellective task that is about solving problems with correct answers. This task is rather conceptual and requires cooperation. Finally, the very last cooperative task that uses the impossible target combination is a decision making task because there is no right answer. In this case, the decision that needs to be made by the participants is to agree that the item does not exist and to announce their decision to the test supervisor.

7.2.4 *Procedure*

After welcoming the participants, the experimenter handed out an information sheet and a statement of agreement to each participant. The information sheet contained details on the camera recording process and how these camera recordings will be utilized in the future. The statement of agreement allowed each participant to individually agree or disagree with public presentations of the recordings. After the statements of agreement had been signed, each participant was randomly associated to one of the three PS colors red, green or blue. Afterwards, all participants filled out a pre-test questionnaire which covered topics like age, body height, field of study, experience with PCs and experience with touch devices. Additionally, each participant stated how well he knew the other participants. When all participants had finished the questionnaire, they were accompanied to the multi-touch table. Depending on the experiment condition, the participants could either choose their position at the table freely (dynamic condition) or they had to stand at a predefined position (static condition). Providing participants of the dynamic condition the possibility of positioning themselves arbitrarily was chosen because this approach best resembles behavior as it would probably occur in a natural setting. On the other hand however, the predefined positioning of participants in the static condition could lead to biased results because the given arrangement could be either advantageous or disadvantageous. In order to overcome this problem, two predefined arrangements for the static condition were selected beforehand. Based on the analysis of spatial patterns from the exhibition (see chapter 6.3.2, one three-sided and one two-sided arrangements have been chosen. The three-sided arrangement is rather disadvantageous because the blue user cannot reach items on the opposite side of the table without bending over it or walking around it. This might also lead to conflicts amongst the participants because there is a high probability for overlaps. The two-sided arrangement on the other hand can be seen as more beneficial because remote areas of the table are reachable from all positions (Fig 19). The two arrangements were balanced across all groups of the static condition.

Before the actual experiment started, an explanation on how to work with the multitouch table and the application was provided. Firstly, the UI, its elements and their functions were presented. Secondly, the initial task was explained to the participants. After a short exploratory phase during which all participants could interact with the UI, the first task started.

When the participants had finished the first task, the second task was explained to them. The explanation was provided in between the two tasks in order to prevent confusion due to the similarity of the tasks. Finally, the second task was conducted.

After all tasks had been performed, a short debriefing took place during which all participants signed their confirmation of participation and received their reward. If desired, the goal and purpose of the research was explained before the participants finally left.

7.3 PARTICIPANTS

A total of 36 participants (12 triads) took part in this study. Each experimental group was assigned to either the static or the dynamic condition. For this condition, each group had to solve both the collaborative and the competitive task. The order of those two tasks were balanced amongst all groups.

The participants were recruited by distributing postings in the university building that contained a short description of the study and an email address to contact. Whenever a person wanted to take part in the study, she was informed of both the general type of the study (group study using a multitouch table) and the camera recordings via email. This information was included because both study type and camera recordings are factors that might prevent participants from taking part in the study. By providing these details to the participants early on, short term cancellations by participants due to unexpected conditions could be avoided.

There were 19 females and 17 males participating in the study. The age of the participants ranged from 19 to 31 years, with an average of 21.86 years (SD=2.32). One participant is a child care apprentice, whereas all others are students at the University of Konstanz coming from different majors (except computer science).

Participants were asked for their experiences with computers in general and in particular with multitouch devices like smart phones or pads. The average score for general computer experience on a five-point Likert scale was 3.92 (SD=0.56), with males scoring a little higher than females (males 4.18, SD=0.58; females 3.68, SD=0.58). From the 36 participants, 22 claimed to own a touch-controlled device (11 male, 11 female). The average score for the participants' experience with touch devices was 2.94 (SD=0.79), again with male participants scoring slightly higher (males 3.23, SD=0.80; females 2.68, SD=0.72). When looking at this data from the viewpoint of owning versus not owning a touch device, owning participants scored on average 3.32 points (SD=0.71) versus 2.36 points (SD=0.65) for the non-owning group.

7.4 DATA ANALYSIS

Data from the experiment was collected and analyzed in multiple ways. The main source for the upcoming analysis are the video recordings and the data that has been derived from them. Besides that, interaction logs as well as notes from the experiment were also employed. The following sections will explain which data has been used for the analysis and how it has been transformed and explored.

7.4.1 *Movement Data*

Even though the tracking system can take care of recording the participants' movements, this data was not utilized for two reasons. First of all, the tracking system is not 100% accurate and might either record non-existing movements or ignore existing ones due to false readings. In addition, the implemented thresholds that are required in order to avoid unsteady PSs also influence the output of the tracking system. Furthermore, the tracking system might detect movements that are no actual movements, e.g. when a participant switches from one leg to another, thereby moving her hips. Most importantly however, relying on the tracking data alone would mean that there is no contextual information on the cause of a movement. Therefore, user movements were analyzed from the video recordings. After synchronizing the three video streams (two external cameras plus screen recording), the videos were analyzed using Noldus Observer XT[1].

Movements were coded using multiple dimensions. First of all, the movement distance was coded. To be able to gain more insightful results, distance was not coded as an absolute measure but as one of four categories. *Short along edge* is every movement where the participant remains at the same side of the table and does not move further than a single step sideways. Such smaller movements often occur unconsciously and might be due to various reasons, e.g because someone adjusting his standing position. The next movement category is named

1 http://www.noldus.com/human-behavior-research/products/2/the-observer-xt – Noldus Observer XT product website. Last accessed 2012-02-28.

Table 3: Examples for the trigger source / trigger type behavior modifiers

		Trigger Source	
		Intrinsic	Extrinsic
Trigger Type	Verbal	A user moves to a new location by herself, whilst or after explaining to the other group members why she does so	A user moves to a new location after another user asked her to do so
	Non-verbal	A user moves to a new location by herself without any accompanying justification	A user moves to a new location either because someone pushes her away or because someone moved closer (too close) to her location

Long along edge and covers all movements beyond a single step as long as the participant remains at the same edge of the table. Since such movements require active walking, they can be considered conscious and intentional. When a user switches from one edge of the table to another (that is, an "around-the-corner" movement), the event is coded as *between edges* movement. Even though the shortest distance around a corner might be smaller than the distance from one end of the long edge to another, this type of movement is considered more significant because it comes with a completely new point of view for the participant and a new arrangement for the entire group. The last category of movement is *between multiple edges*, which covers all movements where a participant walks around at least two corners. Adding more categories for even bigger movements (e.g. distinguishing between movements around two, three, and four edges) was not considered because it was not expected that information gained from these distinctions would yield many benefits. In addition to the distance categories, each movement was coded with multiple modifiers. First of all, the event that causes or precedes a movement, called *Trigger*, was coded. Triggers were categorized using two dimensions. *Source* was the origin of the trigger. A source can either be *extrinsic*, which means that it came from another participant, or *intrinsic*, meaning that the participant decides to move by herself. The second dimension is *type*, which can be either *verbal* or *non-verbal*. The type of a trigger defines how a trigger is communicated amongst participants. Table 3 provides concrete examples for each field of the trigger matrix.

Another modifier is the *goal* of a movement. Here, four categories could be coded: *interaction-focused* movements occur because a participants wants to reach an item or to be in a better position for working with the other group members. When a participant moves because another participant asks her to do so, or because she is too constricted in her interactions, this movement is coded as *people-focused*. A third category is *off-topic*, which applies to all movements that are not related to the task or the group. An off-topic movement for example occurs when a participant moves some distance away from the others because she needs to cough. Finally, it needs to be mentioned that the goal of a movement cannot always be identified clearly from the video recordings because many events might occur at the same time. In such a case, the movement goal has been coded as *unknown*.

The *duration* modifier describes the temporal properties of a movement. Movements can either be *temporary*, meaning the participant is coming back to his original position immediately, or *permanent*, meaning that the participant remains at his new location. Finally, another modifier has been used in order to tag movements that result in a new arrangement of the group. Such a movement occurs as soon as one participant is walking past another one, thereby switching positions. As a result, each participant has a new neighbor. Since the tracking system cannot identify users walking behind other users due to occlusion, the PS of a user who switches her position will vanish entirely from her old position and reappear at her new one.

An additional event besides movements were *lean* event. A lean event occurs when a user leans over the table in order to reach a remote object. These events have been coded because it is assumed that their frequency is lower in the dynamic condition since users are expected to move around the table instead of bending over it. This event does however not include all the various degrees of leaning over the table. In order to reach objects at a medium distance, most users will slightly bend over the table. Such occurrences are not coded. A significant lean event occurs only when a user actively bends over the table, which is usually reflected in either of two typical movements: bending actively over the table while fully extending one's arms and/or lifting one foot from the floor.

The coding results were verified by letting a second researcher code videos from two of the twelve groups and calculating the inter-rater reliability. The resulting value for Cohen's Kappa (Cohen, 1960), which is a statistical measure for inter-rater agreement, is 0.74. According to Landis and Koch (1977), this means a substantial strength of agreement between the two observers.

7.4.2 *Logging Data*

As previously mentioned, the logging data of the tracking system was not utilized in order to derive the movements of participants. However, the log files also contain other interesting data. The log files can be used to analyze how many items a user drags into her PS and at what frequency. Furthermore, the position of each information item is logged before it is dragged into a PS. In this way, the data provides a means to measure the interaction radius of a user.

7.4.3 *Qualitative Data*

There are two sources for qualitative data. The first source are the notes that have been taken during the experiment. Since it is not possible to observe every aspect of a group process, only the most important facts as well as striking observations have been noted. Further qualitative data was recorded during the video analysis. These notes mainly focus on the strategies applied by the groups as well as the communication patterns that occurred. Both aspects could not be quantitatively coded for multiple reasons. The high-level strategies observed during the experiment are very similar and ofter differ only in some very special details. Even though these details are very interesting, it is very hard to create an appropriate and manageable coding scheme for such details. Therefore, the analysis of strategies relies on qualitative data. Initially, it was also planned to quantitatively code the communication amongst group members. However, it turned out that in the given case this effort would not yield appropriate and useful results. Contrary to prior expectancies, only a small number of groups actively communicated about their strategies. Other than that, communication mainly consisted of incoherent deictic references and utterances that did not convey any deeper information. Most of the strategies were developed without discussion simply by trial and error or by imitating other's actions. The only exception to this qualitative approach is communication that is related to movements around the table, since this is covered by the verbal/non-verbal type modifier in the coding scheme.

7.5 RESULTS

This section will present the results of the data analysis, including the quantitative movement data as well as the qualitative data on strategies. An interpretation of these results will then be conducted in the succeeding section.

7.5.1 *Quantitative Analysis*

This section will present quantitative results that are based on the coded video data. After presenting some general figures in order to provide a first overview, more detailed statistics on user movements, task completion times and interaction radii will be unveiled.

General Figures

Table 4 shows how many move events of the different distance categories occurred per condition as well as the corresponding average movements per user. In order to make this first overview as simple

Table 4: Total and average (of all participants) movement and lean numbers for the different conditions

	Total movements	Short along edge	Long along edge	Between edges	Between multiple edges	Lean
Dynamic Total	130 (100%)	90 (69.23%)	8 (6.51%)	25 (19.23%)	7 (5.38%)	58
Static Total	67 (100%)	66 (98.51%)	1 (1.49%)	0 (0.0%)	0 (0.0%)	55
Dynamic Avg. per user (SD)	3.61 (2.71)	5.00 (3.56)	0.44 (0.62)	1.39 (1.54)	0.39 (0.61)	3.22 (2.69)
Static Avg. per user (SD)	1.86 (2.03)	3.66 (5.03)	0.06 (0.23)	0 (0)	0 (0)	3.06 (3.08)

Table 5: Total and average (of all participants) movement and lean numbers for the different task types

	Total movements	Short along edge	Long along edge	Between edges	Between multiple edges	Lean
Collaborative	71 (100%)	63 (88.73%)	6 (8.45%)	2 (2.82%)	0 (0.00%)	40
Competitive	126 (100%)	93 (73.81%)	3 (2.38%)	23 (18.25%)	7 (5.56%)	73

as possible, the table does not distinguish between the different task types. The influence of task type on movement will be analyzed later in this chapter.

Looking at the absolute movement numbers, one can clearly see that much more movements occur in the dynamic setting. A statistical analysis using ANOVA reveals that there exist some significant effects of PS type on the amount of movements. For movements of the short along edge category, there is no effect [F(1,35) = .842, p = .365]. For all other movement categories however, results are significant at the 5% level:

- Long along edge: F(1,35)=6.263; p = .017
- Between edges: F(1,35)=14.655; p = .001
- Between multiple edges: F(1,35) = 7.372; p = .010

Applying the statistical analysis to the total number of all movements, the result is also relevant [F(1,35) = 4.295; p = .046]. Therefore, the main null hypothesis H_{A0} (see chapter 7.1.2) can be rejected. Opposed to expectations however, no significant effect of PS type on the number of leans could be found [F(1,35 = 0.030; p = .864]. This means that the null hypothesis H_{C0} has to be accepted.

Tabke 5 shows the amount of movements grouped by task type. Except for the short along edge category, more movements as well

Table 6: Total numbers and percentages of the *goal* movement modifiers for the different conditions

	Total		Dynamic		Static	
	Count	Percentage	Count	Percentage	Count	Percentage
Interaction-focused	118	59.90	81	62.31	37	55.22
People-focused	1	0.01	1	0.01	0	0.0
Off-topic	36	18.27	16	12.31	20	29.85
Unknown	42	21.32	32	24.62	10	14.93

Table 7: Total numbers and percentages of the *duration* movement modifiers for the different conditions

	Total		Dynamic		Static	
	Count	Percentage	Count	Percentage	Count	Percentage
Temporary	62	31.47	27	20.77	35	52.24
Permanent	135	68.53	103	79.23	32	47.76

as leans occur during the competitive task. However, the statistical analysis showed that this effect is slightly above the 5% level and can therefore only be considered as almost significant [$F(1,71) = 3.518$; $p = .065$] almost significant.

Movement Modifiers

Table 6 and 7 list the total number and relative proportion of movements grouped by the goal modifier and by the duration modifier. Ignoring the unknown events, a majority of movements was interaction-focused for both conditions, followed by off-topic and finally people-focused movements. Looking at the duration modifier percentages, it becomes obvious that permanent movements occur more frequently in the dynamic condition. This effect is also significant [$F(1,196) = 22.405$, $p < .001$].

Looking at table 8, one can see the amount of movements that occurred grouped by the trigger movement modifier. Intrinsic / non-verbal triggers were by far the most common ones, in case of the static condition it is even the only trigger that was observed at all. In the dynamic condition, only a very small fraction of intrinsic / verbal (3.85%), extrinsic / verbal (0.77%) and extrinsic / non-verbal (0.77%) triggers were observed.

Table 8: Total numbers of the *trigger* movement modifier for the different conditions

	Total		Dynamic		Static	
	Intrinsic	Extrinsic	Intrinsic	Extrinsic	Intrinsic	Extrinsic
Verbal	5 (2.54%)	1 (0.51%)	5 (3.85%)	1 (0.77%)	0 (0.0%)	0 (0.0%)
Non-verbal	190 (96.45%)	1 (0.51%)	123 (94.62%)	1 (0.77%)	67 (100.0%)	0 (0.0%)

Table 9: Average interaction radii (in cm) for the different task types and conditions

		Task Type	
		Competitive	Collaborative
PS Type	Dynamic	40.26 (SD=14.99)	37.09 (SD=12.20)
	Static	38.43 (SD=14.23)	34.88 (SD=11.44)

Table 10: Average task completion time (in seconds) for a single item for the different task types and conditions

		Task Type	
		Competitive	Collaborative
PS Type	Dynamic	20.81 (SD=4.89)	43.04 (SD=6.91)
	Static	20.12 (SD=5.73)	40.79 (SD=9.92)

Interaction Radius

Another interesting aspect is how the interaction radius of users changes when they are supported by DPSs. A problem that occurs here is that the interaction radius of a person depends on the size of that person: the taller a user is, the bigger the corresponding interaction radius gets. Since every participant had to provide her body height in the pre-test questionnaire, it was possible to check for this contiguity. To do so, each participant was assigned a size category (short, medium, tall) based on the size distribution of all participants. Afterwards, a statistical analysis was conducted which revealed that there is a significant interaction between body size and interaction radius [$F(2,8537) = 52.455$, $p < .001$]. In order to minimize this effect, the interaction radii for each participant were normalized based on the participant's body height for the statistical analysis. The values contained in table 9 are the unnormalized values such that the table represents the actual results and not the normalized ones.

Statistical analysis of the interaction radii revealed that there is a effect of PS type on the interaction radius [$F(1,8537) = 30.033$, $p < .001$]. However, contrary to expectations the higher interaction radius occurs in the dynamic condition. Hence, hypothesis H_{B0} has to be accepted. There is also an effect of task type on interaction radii [$F(1,8537) = 77.815$, $p < .001$]. Here, the interaction radius is higher for the competitive task type.

Task Completion Times

The average task completion time for a single item is shown in table 10. The table suggests two potential dependencies. Firstly, the task time is higher for the collaborative task than for the competitive task in both conditions. This effect is of course based on the nature of the tasks and was therefore expected in advance. Secondly, the task time is slightly higher for the dynamic condition independent of the task type. This effect is however not significant [$F(1,347) = .204$, $p = .652$]. An effect of PS type on task times was also examined by looking at either the competitive or the collaborative task exclusively. However, this additional analysis did also not reveal any significant effects.

Interpretation of Quantitative Results

The quantitative analysis revealed that there is significantly more movement if users are supported by DPSs. The amount of movements was in turn affected by task type, with more movements during competitive tasks. Since the group members do not work together during the competitive task, each user needs to acquire her own items. In case a user is not within reach of a sufficient amount of items, she has two possibilities: asking other users to hand items over to her, or move to another spot. Groups member in the SPS condition with the three-sided (and for this task disadvantageous) arrangement often asked others to hand items over to them. This behavior did not occur in the dynamic setting. Here, users who recognized that there are no more items within reach would simply move to another place. The amount of leans is also higher for competitive tasks, probably due to the same reason that each user is responsible for her own items and no items are handed over from other group members. Thus, the alternative to moving around the table is leaning over it.

Looking at the goal movement modifier, one can see that a majority of movements is interaction-focused, which is not surprising. Besides off-topic movements, which shall not play a role in this analysis, there was only a single occurrence of a people-focused movement. These movements occur when one user moves away because another users comes to close. Even though there were many movements and rearrangements during the competitive tasks, this type of movement did not play a role. It seems that due to social protocols, people around a table are respecting the private distance zones of others. Therefore, it is usually not required to move away due to another person closing in.

The analysis of the duration movement modifier showed that there are more permanent rearrangements in the dynamic setting. This effect is however quite obvious. When a participant in the SPS condition moves away from her PS, the PS remains at the same spot. Therefore, the participant has to return to her SPS sooner or later in order to continue with the task. In the static condition, mostly short along edge movements occurred, which could mean that users are not inclined to leave their PS. Combined with the prevailing temporary movement modifier, it seems that if participants move away from their PS they will often come back immediately. However, it needs to be mentioned that some users had no problem using their PS whilst standing a short distance away from it. There were not many participants showing this behavior, but those who did made heavy use of it. This is an explanation why nearly 50% of movements in the SPS condition are considered permanent.

More interesting insights can be gathered from the trigger modifier. A clear majority of movements was intrinsic and nonverbal, meaning that participants moved because they decided to do so and without providing any explanation on their behavior. This might be an indicator that rearrangement processes are considered as natural and trivial and therefore the participants did not feel the urge to provide an explanation on their behavior. The fact that other group members did usually not comment on a movement of another user supports this assumption. The fact that movements are seen as an ordinary everyday action supports the approach of DPSs, which support these processes during multi-user interaction around a tabletop.

7.5.2 *Qualitative Analysis*

The qualitative analysis presented in the next sections is based on a close examination of the video recordings. Even though the quantitative data shows that user behavior differs between the collaborative and the competitive tasks, the qualitative analysis did not reveal any further insights relevant for this study. In both conditions, participants acted in a very focused way, most of the time without paying attention to the other group members. The interactions that occurred can be described as mechanical, since each participant's intention was to add as many items successively as possible in order to find the required item. Hence, an assembly-line like working style developed throughout the competitive task. No strategies besides this "add items as fast as possible" behavior could be observed. Interestingly, no conflicts between group members took place except for one group. This group had an intense "fight" over a single item, and all three members showed behaviors like reaching above and below other people's arms, bending heavily over the table and trying to steal an item from another group member. However, this group stated in the questionnaire that they know each other very well, which was confirmed by the impression they made during the experiment. Therefore, the fight might be explained by the fact that the group members knew each other and therefore social barriers were lower as they would be for strangers. Besides this one interesting event, behavior was mostly consistent over groups and conditions. This might be due to the fact that the reward given to the winner (a chocolate bar) did not provide enough motivation in order to evoke more competitive behavior. It might also be due to the fact that participants tried to take part in the study with the smallest possible effort. Therefore, it could be interesting to conduct further studies that analyze competitive behavior in the given scenario with a more motivating reward.

Whereas only sparse insights could be gathered from the competitive tasks, the qualitative analysis of collaborative tasks produced manifold results that will be presented in the following sections.

Occurring Strategies

Throughout the experiment, all groups except one developed and applied different strategies for solving the collaborative task. Interestingly, all of these groups employ some kind of clustering. A detailed analysis of the different clustering approaches will follow in section 7.5.2. Besides clustering, a number of other factors that can be considered an element of a strategy have been identified.

First of all, groups developed different ways of referencing items. Basically, there are three ways in which an item can be referenced: by mentioning its number, by employing demonstrative deictic references, or by gesturing towards an item. Gestures were not employed by any of the groups. This might be due to the fact that usually all participants were working in parallel, thereby using their dominant hand to interact with the touch display. Therefore, people seem to prefer to make a reference to an item verbally such that their work is not interrupted. Furthermore, since there are 21 items on the screen, participants might have anticipated that referencing a single item by gesturing towards it is probably ambiguous and therefore inefficient. References to items were mainly used during handover processes. A common strategy was for a single user to distinguish *positive* (i.e. items containing the wanted symbol) and *negative* (i.e. items with the wrong symbol) items. Whereas negative items were dismissed, positive items were often handed directly to another participant. This handover process was usually accompanied by a short utterance that included a reference to the item. Most of the time, participants would use the item's number to refer to it. However, many participants also referred to the item by mentioning the color and symbol they have seen, even though the contained symbols were hidden after an item has been removed from a PS and thus this kind of reference seems to be irrelevant. For example, a group searches for the target combination "red smiley, green smiley, blue airplane". A participant adds item number 13 to her PS and it reveals a red smiley, which means that the item is positive. When handing this item over to someone else, the participant would either say "thirteen" or "red smiley". Most of the time, these utterances did not directly address another group member. Therefore, it is not directly evident what the purpose of these utterances is. However, a more thorough analysis of these referencing styles revealed that they obviously play an important role for workspace awareness. Normally, each user is working by herself, testing one item after another. As soon as a user identifies a positive item, she hands it over to another user. It seems that social protocols prohibit to directly interfere with another user's action in such a case. Therefore, most users would place the item close to another user's PS and draw her attention by adding an according utterance. The addressed user usually continues working without confirming the preceding utterance or reacting to it otherwise. Nevertheless, this user recorded the incident because the item handed over is usually preferred over others and added as soon as possible. It therefore seems that the combined act of handing an item and referencing it is passively registered by other users who will then utilize this information as soon as they finished their current activity.

Another interesting effect concerning item references can be observed when analyzing these references over the entire duration of an experiment. Using numbers to reference an item is more suitable since colors and symbols can not be seen when items are within the group space. Most participants seemed to be aware of this drawback, since seven out of the twelve groups used numbers for referencing from the beginning. Another four groups used color/symbol references in the beginning, but switched to number references as the task progressed. This can be seen as an indicator that using numerical references is more efficient and therefore most participants switched to this type of referencing after some time. Only a single group predominantly used deictic references ("this one matches") but also used numerical and symbol/color references from time to time.

A further property of the strategies that were observed is concurrency. Participants worked either in a sequential, parallel or mixed way. Working sequentially means that a single user starts to add items while the others are watching. As soon as a positive item is identified, it is handed over to the next user and so on. The advantage of this approach is that there is a clear order of actions that avoids interaction conflicts. Furthermore, intermixing positive and negative items due to the parallel activities on the table does not occur. However, this approach is highly inefficient since most only a single user is interacting at any time. In a parallel approach, all participants add items simultaneously. This method is very efficient, however it provides more possibilities for conflicts and item mix ups. The mixed approach was observed a number of times and combines sequential and parallel working. In the beginning, all participants work in a parallel way. As soon as one user identifies a positive item, the other group members stop inspecting new items and check the positive item first. Six out of twelve groups worked in a parallel way from the beginning. Two more groups started with a sequential approach, however they soon became aware of its inefficiency and therefore also switched to a parallel strategy. Four groups mainly used the mixed strategy, however some of them also switched to a parallel strategy from time to time.

Strategy Development and Evolution

The strategies applied by the single groups usually evolved over some time, and different mechanisms for developing a strategy were observed. All but one group applied different clustering strategies whilst working on the task. The details of these strategies will be discussed in the next section. Six out of the twelve groups developed their strategy in a seemingly automatic way without much communication just by solving the task repeatedly. It was observed that imitation sometimes played a role in adapting a common strategy. Most of the time, a single user would have the idea to create clusters of some kind. Even if this approach was not communicated to the other group members, they would eventually adapt it given that the strategy they observed is successful.

Another way of developing a strategy was that a single user makes a proposal which is then adapted by the group. This was observed for four groups in total. However, the strategy that was proposed initially was often adapted in the course of time. Hence, one cannot say that a single person determined the group's strategy. Rather than that, a single user provided an initial impulse for developing a strategy which was then advanced by the entire group.

Finally, two groups relied on intense discussions in order to derive a strategy. These discussions usually took place in between two items, and during the time of discussion no further tasks were solved. However, users did interact during the strategy development phase in order to illustrate a possible approach to the other group members.

The clustering strategies have evolved in a seemingly natural way and often without actively discussing a strategy. Clustering was mainly applied for negative items, whereas positive items were directly handed over to another group member. In four out of twelve cases, clustering of negative items was proposed by a single group member at some point. Only thereafter did the other group members also employ clustering, usually accompanied by a statement like "this is a good idea, let's do this". Five groups applied clustering without any direct communication taking place. However, it could be observed that imitation seems to play an important role in this process. In multiple instances, a single participant started to cluster items and after some time, the other group members adapted this approach by imitating and sometimes refining it. Two groups developed their strategy by actively discussing it amongst all group members. This could happen either at the beginning or between tasks. In this context, one group was especially notable. This group started working on the task immediately and identified the first three items. After the fourth target item had been presented, the group started discussing a strategy for over three minutes during which they (verbally) covered nearly all of the aforementioned clustering alternatives. There was one person leading the discussion who was obviously focused on elaborating a finished strategy before continuing. At the end, the group started with a sequential strategy where positive items would be handed from one participant to the next one in an assembly-line like fashion. However, the group dismissed this strategy after a very short time because they underestimated the inefficiency of the sequential approach. They then implemented a parallel strategy with local clusters, which was very similar to the strategy the group employed automatically in the beginning.

Clustering Approaches

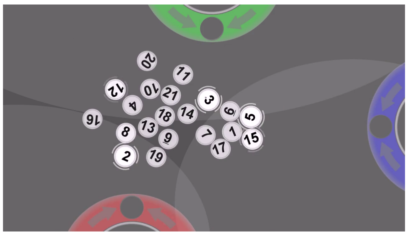
All except one group applied some type of clustering in order to structure the task. Clusters were established simply by placing multiple items close to each other (Figure 20). Based on the observations, clusters can be categorized in two dimensions. *Cluster ownership* describes who can access and manage a cluster. Clusters can have one of two ownership types:

- *Public clusters* can be accessed by all group members. They are usually located such that at least two of the three group members can easily access them.
- *Private clusters* are created, accessed and maintained by a single user. They are usually located directly in front or next to the owner's PS.

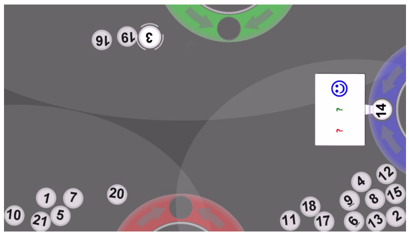
The other dimension that has been identified is *cluster content* and describes what kind of items are contained in a cluster. These can be:

- *New items* that have not been checked by any group member so far.
- *Positive items* that have been checked by one or two group members and so far match the target symbol combination.
- *Negative items* that have been checked and do not match the target symbol combination.
- *Sorted negative items* that contain items with one identical symbol that is however not the target symbol.

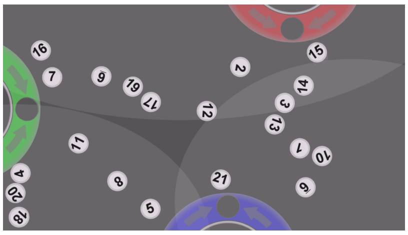
The last mentioned class (sorted negative items) requires some further explanation. Given the case that a group is looking for the symbol combination "red smiley, green smiley, blue airplane", the participant owning the red PS might apply clustering as follows: if the item contains a smiley (target symbol), it is transferred to the public new items cluster. If it contains an airplane, it is moved to a private sorted negative items cluster that only contains red airplanes. If it contains a pen, it is moved to a private sorted negative items cluster that only contains red pens. This approach is a bit more complicated since the owner needs to remember which cluster contains which symbol and since it requires two clusters. However, it is highly efficient because the owner can immediately declare an entire cluster as positive or negative when a new target combination is presented. An example for this approach can be seen in Figure 20d, where the green and blue users have established two private sorted negative item clusters.



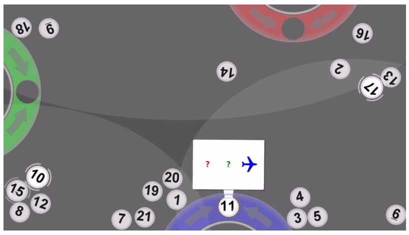
(a) *Cluster fusion*: initial cluster of all items upon a task's beginning (group 3).



(b) Final clustering consisting of three *private negative item* clusters (group3).



(c) Initial layout of items after randomizing their positions (group 7).



(d) Final clustering. Green and blue use two *private sorted negative item* clusters each, red uses a single *private negative items* cluster (group 7).

Figure 20: Two examples for applied clustering strategies

It was also observed that groups carried out different actions after the target item has been found and a new symbol combination has been presented. A common approach was to break up all clusters and put all items into a big public new items cluster that was located in the table center. Afterwards, each participant would take one item after another from this cluster in order to process it. This approach will be called *cluster fusion* (Figure 20a). Another method, that will be referred to as *cluster switching*, occurred sometimes when private clustering was applied. Usually, participants created their private negative cluster on one side of their PS. When a new target item was presented, the items contained in this cluster were controlled first. Negative items were however not returned to the original negative cluster but to a new negative cluster on the other side of the user's PS. In this way, the private negative cluster switches between two positions (usually left and right of the PS) with each new item.

The distinctions presented so far are not mutually exclusive. Some groups mixed different approaches or switched from one method to the other in the course of the experiment. A combination of private and public clusters for negative items was observed multiple times, especially when one of the group members was located such that her operating range on the table was limited. This mostly occurred when a user was located at the short edge of the table. In such cases, the user with a limited range would create a private negative cluster whilst the two other users would create a public negative cluster.

The clustering strategies have evolved in a seemingly natural way and often without actively discussing a strategy. Clustering was mainly applied for negative items, whereas positive items were directly handed over to another group member. In four out of twelve cases, clustering of negative items was proposed by a single group member at some point. Only thereafter did the other group members also employ clustering, usually accompanied by a statement like "this is a good idea, let's do this". Five groups applied clustering without any direct communication taking place. However, it could be observed that imitation seems to play an important role in this process. In multiple instances, a single participant started to cluster items and after some time, the other group members adapted this approach by imitating and sometimes refining it. Two groups developed their strategy by actively discussing it amongst all group members. This could happen either at the beginning or between tasks. In this context, one group was especially notable. This group started working on the task immediately and identified the first three items. After the fourth target item had been presented, the group started discussing a strategy for over three minutes during which they (verbally) covered nearly all of the aforementioned clustering alternatives. There was one person leading the discussion who was obviously focused on elaborating a finished strategy before continuing. At the end, the group started with a sequential strategy where positive items would be handed from one participant to the next one in an assembly-line like fashion. However, the group dismissed this strategy after a very short time because they underestimated the inefficiency of the sequential approach. They then implemented a parallel strategy with local clusters, which was very similar to the strategy the group employed automatically in the beginning.

When looking at Figure 20d, one can see that private clusters were established directly next to a user's DPS. This is plausible, since private clusters belong to a single user and are therefore exclusively accessed by her. One could also say that by arranging items around a DPS it is extended into the group space. Depending on the task and application at hand, it might therefore be beneficial to support the creation and arrangement of clusters within a DPS. In this way, users can take their clusters with them when moving around the table. Furthermore, by providing appropriate clustering methods and visualizations, a high number of clusters can be managed. Finally, the border between group space and personal space becomes more clear when including clusters

Figure 21: Example of a user invading another user's DPS.

into a DPS (which was not always the case during the study, see for example Figure 20d, item 6 and 14).

Intrusion of Personal Spaces

The results of Kruger et al. (2003), who observed that people do not interact within the PS of other group members, could be verified during this study. However, there was a small number of incidents where PS intrusion occurred (e.g. Figure 21). A number of occurrences took place when the group had been searching for an item for a long time and only a single item was left. This situation seemed to lead to an increased tension amongst group members because they wanted to know if this item is the right one, or if they might have accidentally ruled out the correct one. In such cases, it sometimes occurred that one participant would add an item to another participant's DPS. However, this behavior only took place when that one user was the last one who had to confirm the item. Therefore, this intrusion of a DPS might be attributed to the increased tension and curiosity amongst group members and the drive to finish the task as quickly as possible.

In one case, the blue and green participants invaded each other's DPS. The video analysis revealed that some minor verbal exchanges between those two group members occurred beforehand that had a clearly negative undertone. Whilst discussing a strategy, the green participant removed an item from the blue participant's DPS in order to place all items in the center of the table. This action did however not lead to any reaction. However, at a later point the blue participant was intruding the green participant's DPS multiple times by adding positive items. Due to the foregoing subliminal verbal conflict between these two participants, one might argue that this DPS intrusion occurred intentionally in order to further annoy or irritate the other group member. Since the blue participant was constantly ignoring common social protocols, this conflict was resolved through the green participant by verbally prohibiting the blue participant to interact directly with her DPS.

Even though the intrusion of DPSs is not the focus of this study, these observations suggest that the inhibiting threshold that avoids intrusion of other people's PS gets lower with increasing arousal. This arousal can be either positive (as in the first example because of curiosity) or negative (as in the last example because of interpersonal conflicts).

7.6 Summary of results

We have seen that by providing a technology that supports movements around a tabletop, users will employ this technology in a very natural way. It is assumed that the possibility of moving around a table freely allows for more common behavior, since users are not restricted by a default position that is determined by the system's design. Therefore, the main null hypothesis H_{A0}, which stated that the application of Dynamic Personal Spaces does not lead to an increased amount of movement, could be rejected. The secondary null hypotheses H_{B0} and H_{C0}, which stated that the application of DPSs will not decrease the interaction radius or the amount of leans, could not be rejected. This might be a hint to some kind of internal process that compares the advantages of moving to another spot with the advantages that emerge when staying in one location and leaning over the table instead.

The qualitative analysis revealed that strategies for solving a group task often evolve by applying some initial strategy and refining it over multiple iterations. Here, imitation plays also an important role for the quick and effective adaption of a successful strategy. Furthermore, the study revealed that users make heavy use of clustering items. Private clusters were created directly next to a PS, such that they functioned as an extension of this space. Finally, a couple of incidents were participants invaded another participant's PS were observed. The analysis suggests that this ignoring of social protocols might be connected to arousal. Increased arousal would then lead to a reduction of the inhibiting threshold which keeps users from interfering with another PS.

Based on the analysis of log files from the exhibition and on the evaluation in the lab, a number of basic design guidelines for DPSs can be derived. These guidelines will be presented in the next chapter.

8 DESIGN GUIDELINES FOR DYNAMIC PERSONAL SPACES

Visibility of Dynamic Personal Spaces

A problem that was observed during the first exhibition part was that the DPSs were not recognized as such by the visitors. This is an elementary problem that should be avoided in all cases because recognizing a DPS as such is a prerequisite for all other interactions with the system. The effect that occurred in the first exhibition part can probably be attributed to the visual design of the DPS, which had a small size and transparent background color. Therefore, DPSs should be designed such that they are clearly distinguishable from the group space. One can think of other methods that can be added in order to draw the user's attention, e.g. using an initial animation. Furthermore, a DPS should be designed such that it conveys a direct connection to the user. Otherwise, a user might well become aware of a DPS but nevertheless overlook the fact that it is connected to the user's presence. Such a visual connection can for example be created by using a geometrical shape for the DPS that is truncated along the edge where the user is located. Because people usually follow the law of closure[1] , they will complete the truncated shape in their minds. The resulting shape will then virtually surround or enclose the user, thereby conveying that the user is a part of it. This approach has been implemented in both museum exhibitions where DPSs are visually represented as a truncated torus (first part) or circle (second part).

Independence of Dynamic Personal Spaces and Objects in the Group Space

The application used in the first part of the exhibition made heavy use of physical properties for virtual objects. Thus, information items as well as DPSs had physical properties such that they could collide with each other. Whereas this was no problem in the exhibition because users were interacting in parallel and without a need for organizing the items, it turned out to be an issue during the evaluation. There, it occurred that participants would establish one or two private clusters very close to their DPS. As soon as a participant moves however, the items are pushed away by the moving DPS and the clusters are destroyed. This might also be a reason why participants did not move as much as expected because the advantage of moving around does

1 The law of closure is a gestalt principle that describes the "tendency to complete or close an incomplete part or whole so as to attain maximum simplicity or stability" (Corsini, 2002, p. 537)

not outweigh the disadvantage of having to build new clusters every time. Therefore, DPSs should be implemented such that they do not interact with objects in the group space (unless intended). An easy approach to this issue would be to put the DPSs into an extra layer that resides on top of the group space. In this case however, one has to make sure that DPSs do not occlude items located directly below them. Here, some automatic layout mechanisms should be implemented which take care of such issues.

Low Threshold, High Ceiling

The analysis of log data from the exhibition revealed that the way in which items could be added to a DPS (drag and drop versus tap) had a significant effect on the learnability of the system. Even though one might think that drag and drop can be considered an everyday paradigm, data suggests the opposite. Nonetheless it is crucial that users can access a system quickly and easily because initial frustrations quickly make users give up on the system. This is especially true in public settings, where a wide variety of users has to be expected. Therefore, the threshold for initial interactions with a DPS should be as low as possible. On the other hand, there are experienced users who will expect more elaborate and sophisticated functionality from a DPS. Such functionality should also be supported in order to support more professional requirements. For example, users might wish to exchange digital objects between their DPS and their smart phone. Such advanced features should not clutter the DPSs primary interface with respect to novice users. Nevertheless, they should be easily accessible in order to provide an appropriate level of usability. Even though low ceiling and high threshold are not entirely mutually exclusive, there might be scenarios that require a decision in favor of one or the other. This mainly depends on the application and the targeted user group, such that the decision needs to be made case by case.

Support organization of Dynamic Personal Space contents

We have seen that the study participants made excessive use of clustering during the collaborative task. It therefore seems that clustering is a fundamental process to group work and should therefore be supported appropriately. But even though clustering is important, users should be able to deposit items such that they still have enough space within their DPS to interact. Taking the circular DPS design from the study as an example, one could think of a two-zone implementation. The inner zone of a DPS is used for interacting with task resources and executing the main task. The outer zone serves as a storage area within which reserved but currently unneeded items can be deposited and clustered. In order to minimize display space requirements, the outer zone can be expanded or collapsed by the user. In this way, the advantages of clusters, clustering methods and DPSs can be combined into a single construct.

These design guidelines shall serve as an advice when implementing DPS-based applications. However, due to the foundational character of the study and because the DPS approach cannot yet be considered mature, this list of guidelines sis not yet exhaustive. Nevertheless, they can be used as a starting point for researchers who want to develop and evaluate DPS-based applications.

Part III

APPLICATION AND OUTLOOK

Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning.

- Winston Churchill

9 ESTABLISHING A DESIGN SPACE FOR USER TRACKING AROUND TABLETOPS

The evaluation of the tracking system and DPSs in the previous chapter showed that people make use of the possibility to move around an interactive tabletop freely if this movement is supported by the system. However, this evaluation is very basic, addressing only the fundamental aspects of this technology - "to use or not to use". Nevertheless, a tabletop-integrated tracking system provides many more possibilities. On the one hand, it can be used to enhance existing approaches and interaction techniques. On the other hand, it also allows for completely new applications. Both aspects will be covered in this chapter, which will thereby establish a design space for user tracking around tabletops.

9.1 A COLLECTION OF APPLICATIONS BASED ON USER TRACKING

In the following, a number of applications and use cases based on user tracking will be presented. Each of these applications is described using a short abstract, a more detailed description, a summary of its limitations as well as references to related research. The sum of all of these applications forms a continuum in multiple ways. Firstly, applications described in the beginning are rather simple, whereas those towards the end become more elaborate. Secondly, the initial applications can be employed for single user settings (even though they also work for multiple users), whereas the later ones are intended for multi-user scenarios.

Context-Aware Power Management

Abstract:	The tabletop switches its components on and off automatically, depending on the presence of a user.
Description:	Whenever the system detects the presence of a user, it will switch on all its components automatically. As long as a user is present, the system will avoid any kind of automatic power saving, e.g. switching off the screen after a certain time of inactivity. When the user leaves, the system can instantly switch back to a power saving state. In this way, the tracking system allows for less power consumption, less time for starting up the system, and increased lifetime of components.
Limitations:	This technique should not be applied in situations where the tabletop is accessible by novice users because they might become aware of the system's apparent "off" state from a distance and thus not approach the table at all.
Related Work:	Harris and Cahill (2005); Harle and Hopper (2008)

Automatic Document Orientation

Abstract:	Documents presented on the tabletop are automatically oriented towards the user.
Description:	One property of tabletops is that they can usually be accessed from every direction. Since the system knows where a user is located, it can automatically orient documents towards the user, thereby reducing the user's workload.
Limitations:	If there are multiple users, the system is usually not able to assign documents and interactions to a specific user. This also impedes the automatic orientation of documents. One solution is to apply a set of heuristics that estimate which document belongs to which user. Another solution is to make use of Dynamic Personal Spaces as document container. This container will then take care of orienting documents appropriately. Furthermore, there should be a possibility to override automatic orientation.
Related Work:	Kruger et al. (2003); Shen et al. (2004); Hancock et al. (2006); Liu et al. (2006)

Abstract:	Novice users can be motivated to interact with the tabletop by means of dynamic lures.
Description:	One problem of publicly installed tabletops is the novelty of such systems. Tabletops can not yet be considered an everyday technology. Thus, users approaching a tabletop might be confused about the purpose of such a system and what to do with it. By means of user tracking, a tabletop system can dynamically lure arriving users. These lures can be designed to introduce users to the system and motivate interactions. A simple example is a basic welcome message that is displayed in front of a user when she approaches the table (e.g. "Welcome! Please touch an icon to begin."). Using dynamic lures instead of static ones can have a number of advantages. First of all, users might feel a higher degree of involvement with the system because it actually responds to their presence. Secondly, dynamic lures allow for diverse implementations, e.g. using auditive elements. This is not feasible for static systems since it would require constant playback of the audio file. Finally, visual lures can be designed freely because they appear and disappear dynamically and therefore do not clutter the interface, as would be the case with static ones.
Limitations:	None.
Related Work:	Brignull and Rogers (2003); Hornecker et al. (2007)

Abstract:	Data from the tracking system can be used to monitor the number of users, session durations, and other numerical measures.
Description:	When installing a tabletop system in public spaces like a museum or a trade fair, one might be interested in statistics concerning the usage of the system. Traditional interaction logging is one solution, however this data can not reveal everything: does a long phase of inactivity mean that one user left and another arrived, or does it mean that one user temporarily discontinued his activities? Are there any users who are simply standing at the table without interacting at all? Such questions can be answered using the data from the tracking system.
Limitations:	Identifying bystanders (user who do not interact at all) is only possible during single user periods, since during multiuser periods interactions cannot be assigned to specific users (see also *Automatic Document Orientation*. Furthermore, the data does not include people who were looking at the tabletop from a distance or from behind another person. Finally, the tracking system cannot provide proper statistics during crowded situations because multiple users standing together are perceived as a single blob by the system. Even though one can be sure that at a given blob size there must be more than one user, deriving an exact number is not possible.
Related Work:	Nitsche (2011b)

Interaction Logging

Abstract:	Dynamic personal spaces allow logging interaction data on a per-user basis.
Description:	When interactions with a personal space or with an element within a personal space occur, they can be attributed to a specific user. This is not possible when relying on a standard multitouch application because the system does not even know how many users there are. Therefore, dynamic personal spaces allow for a user-based interaction logging, which can increase the expressiveness of the data collected.
Limitations:	A 100% confidence of attributing interactions to a specific user is not given at all times. Ambiguous results may for example occur when two users are located next to each other and interact within each others personal space.
Related Work:	Hilbert and Redmiles (2000); Gerken et al. (2008); Nitsche (2011b)

Dynamic Display Partitioning

Abstract:	Dynamic personal spaces are a means of dynamically partitioning screen estate amongst all users.
Description:	When interactions with a personal space or with an element within a personal space occur, they can be attributed to a specific user. This is not possible when relying on a standard multitouch application because the system does not even know how many users there are. Therefore, dynamic personal spaces allow for a user-based interaction logging, which can increase the expressiveness of the data collected.
Limitations:	The number of personal spaces available is restricted by two variables. Firstly, screen size and screen resolution influence how many personal spaces can maximally be displayed in parallel without being useless. Secondly, the accuracy of the tracking systems and the algorithms employed restrict the maximum number of personal spaces that can be tracked.
Related Work:	Scott et al. (2003); Tse et al. (2004); Scott et al. (2004)

Private Toolbars and Menus

Abstract:	Toolbars and Menus can be displayed dynamically for each user in order to improve parallel interactions.
Description:	Many applications rely on some kind of menu or toolbar in order to control the available functions. Usually, menus are displayed continuously at a fixed position whereas toolbars can be switched on and off and moved to different positions. This paradigm is well-suited for desktop applications, however a number of problems occur when applying it to tabletop applications. First of all, users may position themselves at any location around the tabletop. A fixed menu therefore means that users might have to read menu items upside down or that these menu items are not within reach from the user's position. Secondly, physical and psychological conflicts may arise during multiuser sessions when multiple users try to access a menu or toolbar item at the same time. These problems can be bypassed with the tracking system: toolbars and menus can be multiplied, depending on the number of users, and displayed dynamically at each user's position. In this way, conflicts are avoided while at the same time increasing the readability of the menu items and minimizing the time needed to access a menu item for each user.
Limitations:	Parallel menus and toolbars may lead to conflicts when the offered tools and functions have a global scope. In this case, single users can trigger actions that influence all users alike. A simple example for this is the view mode of a maps application. While there can be only one active view at any time (map, satellite or mixed), different users might prefer different settings.
Related Work:	Morris et al. (2006) Marshall et al. (2011)

Inverse Tracking

Abstract:	A DPS can move by itself in order to motivate a user to move to another spot at the table.
Description:	The idea of "Inverse Tracking" is that a DPS moves by itself in order to motivate a user to move to another spot. One scenario of application is in public settings where many concurrent users are expected. Visitors might not always approach a table such that the space around it is used in an optimal way. A PC can easily calculate an optimal arrangement based on the number of users, their location and the size of their DPSs. If the distribution is suboptimal, a DPS can be animated to move to another place that is more suitable. A user might then follow her DPS, which in turn results in a better arrangement of users that provides a larger working area or that can accommodate more users. If a user does not follow her DPS within a certain time it moves back to the user automatically.
Limitations:	A DPS that moves away from the user might have different negative impacts. Firstly, the user could think that it is a bug rather than a feature and ignore the moving DPS or even leave the table entirely. Another problem is that a moving DPS might confuse users and/or disrupt them in their workflow.
Related Work:	–

Abstract: By combining dynamic personal spaces and user authentication, a tabletop can provide different tools and functions to different users, thereby supporting user roles.

Description: When people work together at a multi-touch table, the users might have different roles. For example in an exhibition fair scenario, there are customers and salesman. Whereas customers should be able to use the system without additional requirements, salesman could optionally authenticate such that they can access special functions of the system. Such functions might be concerned with maintenance (e.g. maintaining digital contents, operating system access) as well as with interactions that are only available to special users (e.g. realigning the contents, switching global views, accessing additional information). With technologies like RFID and NFC, the authorization process can be made very easy. As soon as someone is carrying an NFC tag for example, approaching the table is sufficient because the tag is identified by antennas and the authorization process is executed automatically.

Limitations: By synchronizing data from the tracking system and a tag reader, it is possible to automatize authentication. However, this might not always work, e.g. when two users approach the table at the same time next to each other. In such cases, the system would require a fallback solution, e.g. using traditional login dialogues.

Related Work: Kim et al. (2010)

Arrangement-Based Functions

Abstract:	Different user arrangements around the table trigger different tools and functions.
Description:	Based on the results of Sommer (1965) mentioned in chapter 2.3.2, different arrangements around a table are preferred for different types of dyad activities. For example, most people prefer to sit opposite of each other for competitive tasks, whereas a neighboring arrangement is preferred for cooperative tasks. These results should also be considered when designing multiuser tabletop applications. For example, Hartmann et al. (2009) propose different interaction techniques based on the arrangement of multiple keyboards on a tabletop. When two users are interacting with the system, each user can enter his own search terms with his own keyboard. In this case, the system generates two independent queries. If however the users move their keyboards next to each other, the queries are joined. A similar approach is proposed for multiuser editing of a document. Such behaviors can also be implemented with the tracking system. The system can automatically recognize the arrangement of users and switch between different modes. In this way, the need for explicitly switching modes through user interactions is removed, allowing for a more natural transition between different settings and interactions.
Limitations:	A basic problem underlying this approach is that its functionality is hidden from the user. Therefore, this functionality should either be applied in a setting where all users know about it (e.g. in a closed setting where only a distinct group of trained people uses the system), or it should be communicated to the user in some way. Furthermore, problems might occur when people want to work closely together but without using this functionality. Therefore, such an implementation should allow overriding by the user.
Related Work:	Hartmann et al. (2009)

9.2 APPLICATION OF THE DESIGN SPACE

The previous section has provided a number of applications that can be implemented based on the tracking system and DPSs. A beneficial property of these applications is that they are not mutually exclusive. Instead, as the continuum builds up, more and more possibilities evolve because all of the techniques can be combined. This collection shall serve as a starting point for people implementing applications that are based on the DPS approach. However, it must be clear that this design space is dynamic and therefore evolves over time. As new technologies will be developed and more mature products evolve, new applications will evolve that combine these new technologies with the DPS approach.

10 CONCLUSION

In this thesis, the concept of Dynamic Personal Spaces was introduced. This concept is based on the theory of territoriality, and motivated by research in the fields of HCI and CSCW. Dynamic Personal Spaces are virtual, user-centered territories on an interactive tabletop that appear when a user approaches the table, follow her movements along the table, and disappear when the user leaves the table.

One major part of this thesis dealt with the design and implementation of a tracking system that enables Dynamic Personal Spaces. A first prototype has been in use in a public exhibition for nearly one and a half years, thereby proving the robustness of this system. During this exhibition, logging data from over 4000 user sessions has been collected and analyzed. The evaluation of logging data allowed a thorough analysis of spatial patterns for different group sizes that occur around a multi-touch table in a public setting. Furthermore, the data suggests that public systems should have the lowest possible initial threshold for using them, such that users can start working with them right away. Finally, the data revealed that users seem to make use of Dynamic Personal Spaces since movements around the table occurred on a regular base. However, the data could not provide contextual information or insights into the underlying processes of user movement. Therefore, a laboratory study was conducted which focused on these underlying processes. By comparing Static and Dynamic Personal Spaces during a collaborative and a competitive task, the study revealed that users do move around a table during group work if they are supported by the system. It seems that user movements are a natural process that is however inhibited when the user position is prescribed by the system. A qualitative analysis revealed some further insights. Concerning Personal Spaces, a theory could be developed stating that social protocols that avoid intrusion into other people's Personal Space are less effective when group members are in a state of arousal. Besides, the qualitative analysis showed how people employ clustering during collaboration, suggesting that this is a fundamental process that should be supported by collaborative systems. Based on the results of the two evaluations, a number of initial design guidelines for Dynamic Personal Spaces have been developed. Finally, a design space for Dynamic Personal Spaces has been developed which features a number of proposals for enhancing existing interaction paradigms and for implementing new ones.

The main contribution of this thesis is the implementation and evaluation of Dynamic Personal Spaces. The work presented builds a thorough basis for future research: on the one hand, there is a robust implementation of a tracking system that can be employed in a variety of settings. On the other hand, the guidelines and use cases presented at the end provide a starting point for future research. This future research will hopefully not only produce some more interesting insights, but most importantly lead to better products, to new interaction styles for groups, and last but not least to systems that support co-located collaboration in a natural and seamless way.

BIBLIOGRAPHY

Altum, B. (1868). *Der Vogel und sein Leben*. Heinrich Schöningh, Münster, DE.

Bannon, L. J. and Schmidt, K. (1989). Cscw: Four characters in search of a context. In *Proceedings of the First European Conference on Computer Supported Cooperative Work*, ECSCW '89, pages 358–372, Gatwick, London.

Berthold, M. and Hand, D. (1999). *Intelligent Data Analysis. An Introduction*. Springer.

Brignull, H. and Rogers, Y. (2003). Enticing people to interact with large public displays in public spaces. In *In Proceedings of the IFIP International Conference on Human-Computer Interaction (INTERACT '03)*, pages 17–24. IOS Press.

Brna, P. (1998). Models of collaboration. In *Proceedings of the Workshop on Informatics in Education, XVIII Congresso Nacional da Sociedade Brasileira de Computação Rumo à Sociedade do Conhecimento*, Belo Horizone, Brazil.

Cohen, J. (1960). A coefficient of agreement for nominal scale. *Educational and Psychological Measurement*, 20:37–46.

Collins, A., Ackad, C. J., Apted, T., Sztajer, P., Ward, P., Weng, H., and Kay, J. (2011). Core functionality and new applications for tabletops and interactive surfaces. In *Proceedings of the 13th international conference on Ubiquitous computing*, UbiComp '11, pages 607–608, New York, NY, USA. ACM.

Cool, M. (1970). Experiments on orientation and proxemics. *Human Relations*, 23(1):61–67.

Corsini, R. J. (2002). *The dictionary of psychology*. Psychology Press.

Cummings, L. L., Huber, G. P., and Arendt, E. (1974). Effects of size and spatial arrangements on group decision making. *The Academy Management Journal*, 17(3):460–475.

Dietz, P. and Leigh, D. (2001). Diamondtouch: a multi-user touch technology. In *Proceedings of the 14th annual ACM symposium on User interface software and technology*, UIST '01, pages 219–226, New York, NY, USA. ACM.

Dourish, P. and Bellotti, V. (1992). Awareness and coordination in shared workspaces. In *Proceedings of the 1992 ACM conference on*

Computer-supported cooperative work, CSCW '92, pages 107–114, New York, NY, USA. ACM.

Fitzmaurice, G. W., Ishii, H., and Buxton, W. A. S. (1995). Bricks: laying the foundations for graspable user interfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, CHI '95, pages 442–449, New York, NY, USA. ACM Press/Addison-Wesley Publishing Co.

Gerken, J., Bak, P., Jetter, C., Klinkhammer, D., and Reiterer, H. (2008). How to use interaction logs effectively for usability evaluation. In *Beyond time and errors: novel evaluation methods for information visualization (a CHI 2008 Workshop)*, BELIV'08, Florence, Italy.

Geyer, F., Pfeil, U., Höchtl, A., Budzinski, J., and Reiterer, H. (2011). Designing reality-based interfaces for creative group work. In *Proceedings of the 8th ACM Conference on Creativity and Cognition, Atlanta, USA*, C&C'11, pages 165–174. ACM Press.

Gutwin, C. and Greenberg, S. (1998). Design for individuals, design for groups: tradeoffs between power and workspace awareness. In *Proceedings of the 1998 ACM conference on Computer supported cooperative work*, CSCW '98, pages 207–216, New York, NY, USA. ACM.

Hall, E. T. (1966). *The hidden dimension*. Doubleday, Garden City, NY, USA.

Han, J. Y. (2005). Low-cost multi-touch sensing through frustrated total internal reflection. In *Proceedings of the 18th annual ACM symposium on User interface software and technology*, UIST '05, pages 115–118, New York, NY, USA. ACM.

Hancock, M. S., Carpendale, S., Vernier, F. D., Wigdor, D., and Shen, C. (2006). Rotation and translation mechanisms for tabletop interaction. In *Proceedings of the First IEEE International Workshop on Horizontal Interactive Human-Computer Systems*, pages 79–88, Washington, DC, USA. IEEE Computer Society.

Harle, R. K. and Hopper, A. (2008). The potential for location-aware power management. In *Proceedings of the 10th international conference on Ubiquitous computing*, UbiComp '08, pages 302–311, New York, NY, USA. ACM.

Harris, C. and Cahill, V. (2005). Exploiting user behaviour for context-aware power management. In *IEEE International Conference on Wireless And Mobile Computing, Networking And Communications*, volume 4 of *WiMob*, pages 122–130. IEEE.

Hartmann, B., Ringel Morris, M., Benko, H., and Wilson, A. D. (2009). Augmenting interactive tables with mice & keyboards. In *Proceedings* *of the 22nd annual ACM symposium on User interface software and technology*, UIST '09, pages 149–152, New York, NY, USA. ACM.

Heape, W. (1931). *Emigration, migration and nomadism*. W. Heffer and Son Ltd., Cambridge, UK.

Hearn, G. (1957). Leadership and the spatial factor in small groups. *Journal of Abnormal and Social Psychology*, 54:269–272.

Hediger, H. (1955). *Studies of the Pyschology and Behaviour of Captive Animals in Zoos and Circuses*. Butterworths Scientific Publications, London, UK.

Hilbert, D. M. and Redmiles, D. F. (2000). Extracting usability information from user interface events. *ACM Comput. Surv.*, 32:384–421.

Hornecker, E., Marshall, P., and Rogers, Y. (2007). From entry to access: how shareability comes about. In *Proceedings of the 2007 conference on Designing pleasurable products and interfaces*, DPPI '07, pages 328–342, New York, NY, USA. ACM.

Howard, H. E. (1920). *Territory in bird life*. J. Murray, London, UK.

Howells, L. T. and Becker, S. W. (1962). Seating arrangement and leadership emergence. *Journal of Abnormal and Social Psychology*, 64:148–150.

Ishii, H. (2008). Tangible bits: beyond pixels. In *Proceedings of the 2nd international conference on Tangible and embedded interaction*, TEI '08, pages xv–xxv, New York, NY, USA. ACM.

Izadi, S., Brignull, H., Rodden, T., Rogers, Y., and Underwood, M. (2003). Dynamo: a public interactive surface supporting the cooperative sharing and exchange of media. In *Proceedings of the 16th annual ACM symposium on User interface software and technology*, UIST '03, pages 159–168, New York, NY, USA. ACM.

Jetter, H.-C., Gerken, J., Zöllner, M., Reiterer, H., and Milic-Frayling, N. (2011). Materializing the query with facet-streams: a hybrid surface for collaborative search on tabletops. In *Proceedings of the 2011 annual conference on Human factors in computing systems*, CHI '11, pages 3013–3022, New York, NY, USA. ACM.

Jordà, S., Kaltenbrunner, M., Geiger, G., and Bencina, R. (2005). The reactable*. In *Proceedings of the international computer music conference (ICMC 2005)*.

Kim, D., Dunphy, P., Briggs, P., Hook, J., Nicholson, J. W., Nicholson, J., and Olivier, P. (2010). Multi-touch authentication on tabletops. In *Proceedings of the 28th international conference on Human factors in computing systems*, CHI '10, pages 1093–1102, New York, NY, USA. ACM.

Klinkhammer, D., Nitsche, M., Specht, M., and Reiterer, H. (2011). Adaptive personal territories for co-located tabletop interaction in a museum setting. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*, ITS '11, pages 107–110, New York, NY, USA. ACM.

Kruger, R., Carpendale, S., Scott, S. D., and Greenberg, S. (2003). How people use orientation on tables: Comprehension, coordination and communication. In *Proceedings of the 2003 international ACM SIGGROUP conference on Supporting group work*, GROUP '03, pages 369–378, New York, NY, USA. ACM.

Krumm, J., Harris, S., Meyers, B., Brumitt, B., Hale, M., and Shafer, S. (2000). Multi-camera multi-person tracking for easyliving. In *Proc. IEEE Intl. Workshop on Visual Surveillance*, pages 3–10, Dublin, Ireland.

Landis, J. R. and Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, 33(1):pp. 159–174.

Liu, J., Pinelle, D., Sallam, S., Subramanian, S., and Gutwin, C. (2006). Tnt: improved rotation and translation on digital tables. In *Proceedings of Graphics Interface 2006*, GI '06, pages 25–32, Toronto, Ont., Canada, Canada. Canadian Information Processing Society.

Marshall, P., Morris, R., Rogers, Y., Kreitmayer, S., and Davies, M. (2011). Rethinking 'multi-user': an in-the-wild study of how groups approach a walk-up-and-use tabletop interface. In *Proceedings of the 2011 annual conference on Human factors in computing systems*, CHI '11, pages 3033–3042, New York, NY, USA. ACM.

McBurney, D. H. and White, T. L. (2009). *Research Methods*. Examples & Explanations Series. Wadsworth Publishing, 8th edition.

McGrath, J. E. (1984). *Groups: Interaction and Performance*. Prentice-Hall, Inc., Englewood Cliffs, N.J.

Morris, M. R., Paepcke, A., Winograd, T., and Stamberger, J. (2006). Teamtag: exploring centralized versus replicated controls for co-located tabletop groupware. In *Proceedings of the SIGCHI conference on Human Factors in computing systems*, CHI '06, pages 1273–1282, New York, NY, USA. ACM.

Morris, M. R., Ryall, K., Shen, C., Forlines, C., and Vernier, F. (2004). Beyond "social protocols": multi-user coordination policies for co-located groupware. In *Proceedings of the 2004 ACM conference on Computer supported cooperative work*, CSCW '04, pages 262–265, New York, NY, USA. ACM.

Müller-Tomfelde, C. and Fjeld, M. (2010). Introduction: A short history of tabletop research, technologies and products. In Müller-Tomfelde, C., editor, *Tabletops - Horizontal Interactive Displays*, Human-Computer Interaction Series, pages 1–24. Springer London.

Nitsche, M. (2011a). Building a logging-enabled reactive multitouch table for public information exploration. Technical report, HCI Group, University of Konstanz.

Nitsche, M. (2011b). Interaction logging for tabletops. Technical report, HCI Group, University of Konstanz.

Olson, I. C., Atrash Leong, Z., Wilensky, U., and Horn, M. S. (2011). It's just a toolbar!: using tangibles to help children manage conflict around a multi-touch tabletop. In *Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction*, TEI '11, pages 29–36, New York, NY, USA. ACM.

Orr, J. M. and Sackett, P. R. (1991). Outlier detection and treatment in i/o psychology: A survey of researcher beliefs and an empirical illustration. *Personnel Psychology*, 44(3):473 – 486.

Osborne, J. W. and Overbay, A. (2004). The power of outliers (and why researchers should always check for them). *Practical Assessment, Research & Evaluation*, 9(6).

Rekimoto, J. (2002). Smartskin: an infrastructure for freehand manipulation on interactive surfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems: Changing our world, changing ourselves*, CHI '02, pages 113–120, New York, NY, USA. ACM.

Roschelle, J. and Teasley, S. D. (1995). The construction of shared knowledge in collaborative problem solving. In O'Malley, C., editor, *Computer-Supported Collaborative Learning*, pages 69–97. Springer, Berlin.

Saffer, D. (2008). *Designing Gestural Interfaces: Touchscreens and Interactive Devices*. O'Reilly Media.

Schöning, J., Hook, J., Bartindale, T., Schmidt, D., Oliver, P., Echtler, F., Motamedi, N., Brandl, P., and Zadow, U. (2010). Building interactive multi-touch surfaces. In Müller-Tomfelde, C., editor, *Tabletops - Horizontal Interactive Displays*, Human-Computer Interaction Series, pages 27–49. Springer London.

Schwarz, T., Mueller, J., Butscher, S., and Reiterer, H. (2011). Reality-based interaction for control rooms. In *Proceedings of Human Factors and Ergonomics Society Europe Chapter (Poster Session)*, HFSE 2011. Shaker.

Scott, S. D. (2003). Territory-based interaction techniques for tabletop collaboration. In *Conference Companion of the ACM Symposium on User Interface Software and Technology*, UIST '03, pages 17–20. ACM.

Scott, S. D., Grant, K. D., and Mandryk, R. L. (2003). System guidelines for co-located, collaborative work on a tabletop display. In *Proceedings of the eighth conference on European Conference on Computer Supported Cooperative Work*, pages 159–178, Norwell, MA, USA. Kluwer Academic Publishers.

Scott, S. D., Sheelagh, M., Carpendale, T., and Inkpen, K. M. (2004). Territoriality in collaborative tabletop workspaces. In *Proceedings of the 2004 ACM conference on Computer supported cooperative work*, CSCW '04, pages 294–303, New York, NY, USA. ACM.

Shaer, O. and Hornecker, E. (2010). Tangible user interfaces: Past, present, and future directions. *Foundations and Trends in HCI*, 2(1-2):1–137.

Shen, C., Everitt, K., and Ryall, K. (2003). Ubitable: Impromptu face-to-face collaboration on horizontal interactive surfaces. In Dey, A., Schmidt, A., and McCarthy, J., editors, *UbiComp 2003: Ubiquitous Computing*, volume 2864 of *Lecture Notes in Computer Science*, pages 281–288. Springer Berlin / Heidelberg.

Shen, C., Vernier, F. D., Forlines, C., and Ringel, M. (2004). Diamondspin: an extensible toolkit for around-the-table interaction. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, CHI '04, pages 167–174, New York, NY, USA. ACM.

Sommer, R. (1959). Studies in personal space. *Sociometry*, 22(3):247–260.

Sommer, R. (1965). Further studies of small group ecology. *Sociometry*, 28(4):337–348.

Sommer, R. (1967). Small group ecology. *Psychological Bulletin*, 67(2):145–152.

Steinzor, B. (1950). The spatial factor in face to face discussion groups. *The Journal Of Abnormal And Social Psychology*, 45(3):552–555.

Stewart, J., Bederson, B. B., and Druin, A. (1999). Single display groupware: a model for co-present collaboration. In *Proceedings of the SIGCHI conference on Human factors in computing systems: the CHI is the limit*, CHI '99, pages 286–293, New York, NY, USA. ACM.

Streitz, N. A., Geißler, J., Holmer, T., Konomi, S., Müller-Tomfelde, C., Reischl, W., Rexroth, P., Seitz, P., and Steinmetz, R. (1999). i-land: an interactive landscape for creativity and innovation. In *Proceedings of the SIGCHI conference on Human factors in computing systems: the CHI is the limit*, CHI '99, pages 120–127, New York, NY, USA. ACM.

Tang, A., Tory, M., Po, B., Neumann, P., and Carpendale, S. (2006). Collaborative coupling over tabletop displays. In *Proceedings of the SIGCHI conference on Human Factors in computing systems*, CHI '06, pages 1181–1190, New York, NY, USA. ACM.

Tang, J. C. (1991). Findings from observational studies of collaborative work. *International Journal of Man-Machine Studies*, 34(2):143–160.

Tse, E., Histon, J., Scott, S. D., and Greenberg, S. (2004). Avoiding interference: how people use spatial separation and partitioning in sdg workspaces. In *Proceedings of the 2004 ACM conference on Computer supported cooperative work*, CSCW '04, pages 252–261, New York, NY, USA. ACM.

Vaseghi, S. V. (2009). *Advanced Digital Signal Processing and Noise Reduction*. John Wiley & Sons, 4th edition.

Walther-Franks, B., Schwarten, L., Teichert, J., Krause, M., and Herrlich, M. (2008). User detection for a multi-touch table via proximity sensors. In *Proceedings of Tabletop 2008*. IEEE.

Wei, J., Wang, X., Peiris, R. L., Choi, Y., Martinez, X. R., Tache, R., Koh, J. T. K. V., Halupka, V., and Cheok, A. D. (2011). Codine: an interactive multi-sensory system for remote dining. In *Proceedings of the 13th international conference on Ubiquitous computing*, UbiComp '11, pages 21–30, New York, NY, USA. ACM.

Weiser, M. (1991). The computer for the 21st century. *Scientific American*, 265(3):94–104.

Wellner, P. (1993). Interacting with paper on the digitaldesk. *Commun. ACM*, 36:87–96.

Winer, M. and Ray, K. (1994). *Collaboration Handbook: Creating, Sustaining, and Enjoying the Journey*. Amherst H. Wilder Foundation, Saint Paul, Minnesota, 2nd edition.